A holistic flagship towards the 6G network platform and system, to inspire digital transformation, for the world to act together in meeting needs in society and ecosystems with novel 6G services

Deliverable D4.2

Radio design and spectrum access requirements and key enablers for 6G evolution

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Abstract

This report analyses 6G radio design and spectrum access requirements and presents key 6G radio design enablers to be developed within Hexa-X-II WP4. The document includes radio design enablers for flexible, inclusive, sustainable and trustworthy radio, waveforms and modulations, intelligent radio air interface, MIMO transmission, RIS-assisted transmission, flexible spectrum access solutions, joint communication and sensing. The report presents proof-of-concepts on these enablers. The report provides the inputs for the first iteration towards the end-to-end 6G system design in the Hexa-X-II project.

Keywords

6G, radio access, beamforming, waveform, AI-driven air interface design, AI/ML, joint communication and sensing (JCAS), radio access technology, spectrum sharing, FR1, FR2, THz, spectrum access, D-MIMO, channel model

Executive Summary

This report provides an analyse of 6G radio design and spectrum access requirements and presents key 6G radio design enablers to be developed and evaluated within Hexa-X-II WP4. The report provides the inputs for the first iteration towards the end-to-end 6G system design in the Hexa-X-II project. The content of the report is outlined in the following.

Among 6G technological enablers, mmWave and (sub-)THz communications will enable high data rates, up to Tbps speeds with sub-THz frequencies, which will be needed for some specific 6G use cases. However, higher frequencies are prone to molecular level attenuation, impacting propagation and channel modelling. Thus, implementing these systems requires a thorough understanding of the signal's behaviour in every possible new scenario. Furthermore, new link-level modelling and simulations should be developed to fully map the effects of these higher frequencies on different communication systems. Hence, the three main topics have been investigated for highband transmissions: channel modelling, coverage analysis, and link modelling. The channel modelling for sub-THz frequency bands is discussed by providing stochastic and deterministic models to characterize fading, blockage and other propagation phenomena. Next, a coverage analysis of THz communication systems is introduced, considering all propagation losses and other frequency-related challenges. The aim is to estimate the covered area and its impact compared to other frequencies, i.e., 100-300 GHz. Finally, two simulation tools are presented for link modelling, one for the 6G physical layer (PHY), and one for reconfigurable intelligent surface (RIS)-assisted systems. The former plans to understand the performance of the PHY layer processing chain operating in mmWave and sub-THz frequencies. The latter proposes a simulator to investigate the impact of RIS in relayed communication with specific gain and radiation patterns.

Waveform and modulation scheme design for (sub-)THz-based communications are addressed. Waveforms and modulation schemes are the main pillars of spectral and energy efficiency. With multiple carriers, the transceiver can provide higher spectral efficiency and data rates at the cost of increased power consumption. However, this scenario is prohibitive for mobile communications, since the user equipment has energy constraints. Also, as discussed in other chapters, sub-THz-based signals are highly susceptible to attenuation than other frequency bands, requiring more sophisticated energy-saver transceivers. These questions are addressed by analysing traditional waveforms and providing new solutions for sub-THz-based systems. First, the feasibility of mainstream waveforms for 6G systems operating at sub-THz frequency bands is analysed. The objective has been to evaluate the performance of orthogonal frequency-division multiplexing (OFDM) and single carrier (SC)-based waveforms to enable higher data rates and investigate their energy efficiency, phase noise (PN) tolerance, and scalability over high bandwidths. Next, the zero-crossing modulation (ZXM) scheme is proposed to reduce the power consumption of analogue-to-digital converters (ADCs) with 1-bit quantization. Also, polar constellations are introduced for any frequency bands and other scenarios, such as high mobility. The aim is to create a constellation robust to PN and Doppler shift. Finally, learned multi-input multi-output (MIMO) waveforms using AI/ML techniques are presented and their ability to obtain the waveform without pilot detection at the receiver side are discussed.

Intelligent radio air interface design includes enablers for intelligent transmitter with AI/ML functionalities at the transmitter side, intelligent receiver with AI/ML functionalities at the receiver side, and intelligent joint transmitter and receiver design with AI/ML functionalities at both transmitter and receiver to be trained jointly. The intelligent transmitter enablers include AI/ML-based beamforming robust to imperfect CSI estimations, antenna muting to enhance energy efficiency, user pairing for multi-user multi-input multi-output (MU-MIMO) transmission to enhance spectral efficiency, and resource allocation for distributed MIMO (D-MIMO) transmissions to enhance efficiency. The intelligent receiver enablers include AI/ML-based power amplifier non-linearity compensation to enhance energy efficiency and spectral efficiency, channel state information (CSI) prediction to reduce required radio resources for CSI acquisition, and CSI compression to reduce overhead for CSI feedback. The intelligent joint transmitter and receiver design includes learned waveforms for MIMO transmission, learned CSI feedback transmission scheme, learned low-density parity check (LDPC)

encoder and decoder for enhanced energy efficiency, and AI/ML-based MU-MIMO optimization to support diverse devices.

Novel MIMO architectures, i.e., massive MIMO, D-MIMO, and RIS, are fundamental to deploying 6G. These schemes will improve the performance of communications systems by providing a more reliable link and higher throughput with spectral and energy efficiency. Three categories of the enablers are investigated including D-MIMO transmission, massive MIMO architectures, and RIS-assisted transmission schemes. For D-MIMO transmissions, coherent and non-coherent transmissions by providing link-level performance analysis are discussed. Another study approaches the scalability issue due to the increased number of users served by a single processing unit. In this case, an AI/ML-based selection method is proposed to achieve a scalable transmission. Furthermore, the performance of centralized massive MIMO and D-MIMO systems is explored in an indoor industrial scenario for machine-type communication (MTC). Next, cooperative beamforming design is investigated for decentralized transmissions by performing bi-directional training. Other contributions analysed location-dependent coded-caching for MIMO systems, electromagnetic field (EMF) exposure of distributed transmissions at 3.5 GHz, and full digital MIMO architecture for sub-THz frequencies. For the massive MIMO transmissions, hybrid analogue-digital architectures and fully digital architectures to assist sub-THz communication scenarios are presented. Finally, for the RIS-assisted transmission, multiple implementations regarding signal level analysis and control procedures for indoor and outdoor RIS integration are discussed. Other contributions include RIS-assisted D-MIMO system, channel estimation for vehicular communications and integration of reflecting modulation to RIS-assisted systems.

Flexible spectrum access solutions include enablers for spectrum sharing and for low-latency spectrum access. On spectrum sharing, realistic assumptions and models to determine sharing opportunities are explored. Sharing frameworks between non-terrestrial network (NTN) and terrestrial network (TN) are developed that include sharing criteria and selection algorithms, as well as multi- radio access technology (RAT) spectrum sharing solutions that allow a smooth transition from 5G towards 6G. Low-latency random access covers access to sub-THz spectrum considering the high directivity of sub-THz propagation as well as risk-informed random access that takes risk of potential additional interference into account compared to a strict zero-interference approach.

Joint communication and sensing (JCAS), broadly encompassing the ability of the wireless communication system to provide sensing and positioning services, is examined in this deliverable from three key perspectives: JCAS architectures, waveforms and resource allocation, and security and privacy. Concerning architectures, the integration of non-terrestrial networks with the terrestrial segment to enhance positioning capabilities is proposed. Additionally, the combination of monostatic and bistatic sensing for improved integration is suggested. The consideration of multi-static sensing with multiple transmitting or receiving nodes is also included to address the requirement of full-duplex operation in monostatic sensing. Furthermore, the inclusion of jammer detection and localization within the JCAS architectures is explored. In terms of waveforms and resource allocation for monostatic sensing, the optimization of the payload can be achieved through flexible baseband transceivers, while spatial beamforming, even in the presence of hardware impairments, is enabled by the data-driven learning of optimal precoders. Additional degrees of freedom are provided by multi-band processing, along with reduced hardware requirements. The quantification of JCAS power consumption and energy efficiency will also be conducted to ensure efficient operation. In addition to monostatic JCAS, bistatic JCAS is also examined, with a focus on OFDM-based resource allocation, 6D positioning, and inter- user equipment (UE) sensing. Comprehensive coverage of security and privacy is aimed for, considering both a UE-centric and system perspective. Weaknesses are sought to be identified, and necessary requirements are established through this analysis.

Finally, the demonstration of few of these enablers in proof-of-concept (PoC) implementations are presented. The components to be demonstrated include AI-based air interface design, Flexible transceiver design, and JCAS and sensing in a bi/multi-static configuration. These PoCs are intended to show the feasibility of running the developed concepts on real hardware and thus take the technology readiness level (TRL) of the developed concepts a step further.

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Acronyms and abbreviations

Term	Description
2D/3D/6D	Two/Three/Six Dimensional
ACLR	Adjacent Channel Leakage Power Ratio
ADC	Analogue-to-Digital Converter
AFSO	Analogue Free-Space Optics
AI	Artificial Intelligence
AMCM	Adaptive Multi-Carrier Modulation
AoA	Angle of Arrivals
AP	Access Point
ARoF	Analogue Radio-Over-Fibre
ASIC	Application-Specific Integrated Circuit
ASIP	Application-Specific Instruction set Processor
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLER	Block Error Rate
BS	Base Station
C2E	Concept-to-Entity
CC	Coded Caching
CJTs	Coherent Joint Transmissions
cMTC	Critical Machine-Type Communications
CNN	Convolutional Neural Network
CPE	Common Phase Error
CP-OFDM	Cyclic Prefix Orthogonal Frequency Division Multiplexing
CPU	Central Processing Unit
CQI	Channel Quality Indicator
CRB	Cramér-Rao Bound

CRC	Cyclic Redundancy Check
CSF	Channel State Feedback
CSI	Channel State Information
CSIR	Channel State Information at the Receiver
CSIT	Channel State Information at the Transmitter
D2D	Device-to-Device
DAC	Digital-to-Analogue Converter
DFE	Digital Frontend
DFT	Discrete Fourier Transform
DFTS-OFDM	Discrete Fourier Transform Spread Orthogonal Frequency-Division Multiplexing
DL	Downlink
D-MIMO	Distributed MIMO
DPD	Digital Pre-Distortion
DRU	Distributed Radio Unit
DSP	Digital Signal Processor
DSA	Dynamic Shared Access
DSS	Dynamic Spectrum Sharing
E2E	End-to-End
eMBB	Enhanced Mobile BroadBand
EMF	Electromagnetic Field
eType2	Enhanced Type2
EVM	Error Vector Magnitude
FDD	Frequency Division Duplexing
FMCW	Frequency Modulated Continuous Wave
FoV	Field of View
GDP	Gross Domestic Product
HAPS	High Altitude Platform Station

HARQ	Hybrid Automatic Repeat Request
HO	Handover
HW	Hardware
IAB	Integrated Access and Backhaul
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ICRB	Intrinsic Cramér-Rao Bound
IF	Intermediate Frequency
IoT	Internet of Things
JCAS	Joint Communication and Sensing
JT-CoMP	Joint Transmission Coordinated Multi-Point
KPI	Key Performance Indicator
KT-DFT-s-OFDM	Known Tail Discrete Fourier Transform Spread Orthogonal Frequency Division Multiplexing
KVI	Key Value Indicator
LDPC	Low-Density Parity Check
LCA	Life-cycle Assessment
LEO	Low-Earth Orbit
LLR	Log-likelihood ratio
LNA	Low-Noise Amplifier
LoS	Line-of-Sight
LSA	Licensed Shared Access
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
mMIMO	Massive Multiple-Input Multiple-Output
mMTC	Massive Machine-Type Communications
MRC	Maximum Ratio Combining
MRSS	Multi-RAT Spectrum Sharing
MRT	Maximum Ratio Transmission

MTC	Machine-Type Communications
MU-MIMO	Multi-User MIMO
NC-JT	Non-Coherent Joint Transmission
NLoS	Non-Line-of-Sight
NMSE	Normalized Mean Square Error
NR	New Radio
NTN	Non-Terrestrial Network
OFDM	Orthogonal Frequency-Division Multiplexing
OTA	Over-the-Air
PA	Power Amplifier
PHY	Physical Layer
PMI	Precoding Matrix Indicator
PN	Phase Noise
PoC	Proof-of-concept
QAM	Quadrature Amplitude Modulation
QKD	Quantum Key Distribution
QoS	Quality of Service
RAT	Radio Access Technology
RED	Radio Equipment Directive
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
RL	Reinforcement Learning
RM	Reflection Modulation
RMSE	Root-Mean-Square Error
RX	Receive
SA	Standalone
SAR	Specific Absorption Rate

SDG	Sustainable Development Goal
SDR	Software Defined Radio
SFN	Single Frequency Network
SINR	Signal-to-Interference and Noise Ratio
SISO	Single-input and Single-output
SGCS	Squared Generalized Cosine Similarity
SLNR	Signal to Leakage and Noise Ratio
SNDR	Signal to Noise and Distortion Ratio
SNR	Signal-to-Noise Ratio
SoC	System on Chip
SOTA	State-Of-The-Art
STFBCs	Orthogonal Space-Time-Frequency Block Codes
STU	Single Transmission Unit
SU-MIMO	Single-User MIMO
SVD	Singular Value Decomposition
TCM	Trellis Coded Modulation
TN	Terrestrial Network
TRL	Technology Readiness Level
TX	Transmit
UC	Use Case
UE	User Equipment
UEP	Unequal Error Protection
URLLC	Ultra-Reliable Low-Latency Communications
V2X	Vehicle-To-Anything Communication
WP4	Work Package 4
XR	Extended Reality
ZXM	Zero-Crossing Modulation

1 Introduction

This report analyses 6G radio design and spectrum access requirements, provides an overview of the relevant key performance indicators and key value indicators to be used for the assessment of the radio enablers for communication and joint communication and sensing (JCAS). The report presents key 6G radio enablers to be developed within Hexa-X-II work package 4 (WP4), providing inputs for the first iteration of the end-to-end (E2E) system design in Hexa-X-II WP2.

1.1 Objective of the document

The report covers major technological components to be studied in Hexa-X-II WP4 for the design of 6G radio covering wide range of the spectrum ranges from sub-6 GHz to THz. The developed key technology enablers and innovations for addressing physical layer and spectrum sharing challenges will provide inputs and options to 6G end-to-end system design, enabling communications and sensing services in 6G system. The report contributes to the Hexa-X-II WP4 objectives as outlined in the following:

WPO 4.1: Develop an inclusive, trustworthy, and flexible radio design tailored to meet given 6G KPIs and KVI requirements through analysis and integration of HW architectures, transmission schemes and security solutions.

Sustainable, trustworthy and inclusive holistic radio design is discussed (Chapter 2). The 6G key performance indicators (KPIs) and key value indicators (KVIs) requirements for communications and sensing services are defined (Section 2.1, and Section 2.2), with a list of radio enablers for communications and sensing services which contribute to each of these KPIs and KVIs are provided. Representative radio scenarios and corresponding ranges of KPIs are derived based on Hexa-X use cases (Section 2.3). The radio design enablers including *flexible radio design*, *inclusive radio interface*, *sustainable radio solutions*, and *trustworthy radio solutions* to be studied in WP4 are presented (Chapter 3).

WPO 4.2: Provide a suitable channel model and develop novel broadband air-interface techniques to enable energy-efficient operations in the (sub-)THz bands, including new energy-efficient waveforms/modulations and advanced massive MIMO techniques.

The channel models and link models to be developed for transmissions in the sub-THz band are discussed (Chapter 4). The new waveforms and modulations are presented for 6G including orthogonal frequency-division multiplexing (OFDM) -based waveforms, zero-crossing modulation (ZXM), polar constellations, and learned waveforms (Chapter 5). Advanced massive MIMO (mMIMO) architectures and techniques for sub-THz communications are presented including hybrid analogue-digital architecture, and fully digital architecture with low-resolution converters (Section 7.2).

WPO 4.3: Provide solutions that enable flexible, cross-functional joint communication and sensing over a unified radio infrastructure, including new architectures, signals, methods, and protocols.

Joint communication and sensing (JCAS), broadly encompassing the ability of the wireless communication system to provide sensing and positioning services, is examined in this deliverable from three key perspectives: JCAS architectures, waveforms and resource allocation, and security and privacy. Concerning architectures, the integration of non-terrestrial networks (NTN) with the terrestrial segment to enhance positioning capabilities is proposed (Section 9.1.1). Additionally, the combination of monostatic and bistatic sensing for improved integration is suggested (Section 9.1.2 and Section 9.1.3). The consideration of multi-static sensing with multiple transmitting or receiving nodes is also included to address the requirement of full-duplex operation in monostatic sensing (Section 9.1.4). Furthermore, the inclusion of jammer detection and localization within the JCAS architectures is explored (Section 9.3.3). In terms of waveforms and resource allocation for monostatic sensing, the optimization of the payload can be achieved through flexible baseband transceivers, while spatial beamforming, even in the presence of hardware impairments, is enabled by the data-driven learning of optimal precoders (Section 9.2.1, Section 9.2.2, and Section 9.2.3). Additional degrees of freedom are provided by multi-band processing, along with reduced hardware requirements (Section 9.2.4). The quantification of JCAS power consumption and energy efficiency will also be conducted to ensure efficient operation (Section 9.2.7). In addition to monostatic JCAS, bistatic JCAS is also examined, with a focus on OFDM-based resource allocation, six-dimensional (6D) positioning (i.e., three-dimensional (3D) in position and 3D in orientation), and inter-user equipment (UE) sensing. Comprehensive coverage of security and privacy is aimed for, considering both a UE-centric and system perspective. Weaknesses are sought to be identified, and necessary requirements are established through this analysis (Section 9.3).

WPO 4.4: Design intelligent radio air interface to improve one or a combination of KPIs including spectral efficiency, energy efficiency, coverage, or lower cost at FR1 and FR2 spectrum.

The air interface methods including artificial intelligence (AI)-driven air interface design, distributed MIMO (D-MIMO) transmissions, and reconfigurable intelligent surface (RIS)-assisted transmission schemes to be studied are presented in this report.

Intelligent radio air interface design includes enablers for intelligent transmitter with AI/machine learning (ML) functionalities at the transmitter side (Section 6.1), intelligent receiver with AI/ML functionalities at the receiver side (Section 6.2), and intelligent joint transmitter and receiver design with AI/ML functionalities at both transmitter and receiver to be trained jointly (Section 6.3). The intelligent transmitter enablers include AI/ML-based beamforming robust to imperfect channel state information (CSI) estimations, antenna muting to enhance energy efficiency, user pairing for multi-user MIMO (MU-MIMO) transmission to enhance spectral efficiency, and resource allocation for D-MIMO transmissions to enhance efficiency. The intelligent receiver enablers include AI/ML-based power amplifier non-linearity compensation to enhance energy efficiency and spectral efficiency, CSI prediction to reduce required radio resources for CSI acquisition, and CSI compression to reduce overhead for CSI feedback. The intelligent joint transmitter and receiver design includes learned waveforms for MIMO transmission, learned CSI feedback transmission scheme, learned low-density parity check (LDPC) encoder and decoder for enhanced energy efficiency, and AI/ML-based MU-MIMO optimization to support diverse devices.

For D-MIMO transmissions, coherent and non-coherent transmissions by providing link-level performance analysis are discussed (Section 7.1). Another study approaches the scalability issue due to the increased number of users served by a single processing unit. In this case, an AI/ML-based selection method is proposed to achieve a scalable transmission. Furthermore, the performance of centralized mMIMO and D-MIMO systems is explored in an indoor industrial scenario for machine-type communication (MTC). Next, cooperative beamforming design is investigated for decentralized transmissions by performing bi-directional training. Other contributions analysed location-dependent coded-caching for MIMO systems, electromagnetic field (EMF) exposure of distributed transmissions at 3.5 GHz, and full digital MIMO architecture for sub-THz frequencies. For the massive MIMO transmissions, hybrid analogue-digital architectures and fully digital architectures to assist sub-THz communication scenarios are presented.

For the (RIS)-assisted transmission (Section 7.3), multiple implementations regarding signal level analysis and control procedures for indoor and outdoor RIS integration are discussed. Other contributions include RIS-assisted D-MIMO system, channel estimation for vehicular communications and integration of reflecting modulation to RIS-assisted systems.

WPO 4.5: Develop spectrum sharing and medium access mechanisms for enabling an efficient transition to 6G (coexistence) and low-latency service access.

6G spectrum access requirements are discussed (Section 2.4). Flexible spectrum access solutions including enablers for spectrum sharing and for low-latency spectrum access are presented (Chapter 8). On spectrum sharing, realistic assumptions and models to determine sharing opportunities are explored (Section 8.1.1). Sharing frameworks between non-terrestrial network (NTN) and terrestrial network (TN) are developed that include sharing criteria and selection algorithms (Section 8.1.2), as well as multi-radio access technology (RAT) spectrum sharing (MRSS) solutions that allow a smooth transition from 5G towards 6G (Section 8.1.3). Low-latency random access covers access to sub-THz spectrum considering the high directivity of sub-THz propagation (Section 8.2.1) as well as risk-informed random access that takes risk of potential additional interference into account compared to a strict zero-interference approach (Section 8.2.2).

1.2 Structure of the document

This report is structured as follows. Chapter 2 provides an overview of sustainable, trustworthy, and inclusive radio design principles and methodologies. Chapter 2.1 addresses the 6G radio design requirements including the performance requirements measured in terms of KPIs and the value requirements in terms of KVIs. The requirements for both communications and sensing services are outlined. The 6G use cases that are considered, and their associated requirements are presented in this chapter. The chapter includes the list of radio enablers which contribute to each of the KPIs and KVIs, and the list of the radio enablers which are considered for each of the considered 6G use cases. Chapter 3 presents radio design enablers for flexible, inclusive, sustainable, and trustworthy radio. Chapter 5 covers radio channel models to be developed at sub-THz frequencies. The chapter also addresses link-level signal models for 6G physical layer. Chapter 6 presents waveforms and modulations for 6G radio transmissions. Chapter 6 presents radio air interface design leveraging AI/ML methods. The chapter covers methods for intelligent transmitter design, intelligent receiver design, and intelligent joint transmitter and receiver design. Chapter 7 presents the enablers for MIMO transmissions including D-MIMO architectures and methods, mMIMO architectures and methods, and RIS-assisted transmission schemes. Chapter 8 addresses flexible spectrum access solutions including methods for spectrum sharing and coexistence, and methods for low-latency random access. Chapter 9 covers radio enablers for joint communications and sensing. The chapter presents architectures, waveforms, frame structures, and recourse allocations for JCAS, and covers topics related to the security and privacy of the JCAS. Chapter 10 presents the demonstrations for the proof-of-concept assessments of the developed enablers in WP4.

2 Sustainable, trustworthy and inclusive holistic radio design

In the context of mobile communications systems, radio design refers to the process of creating a radio frequency (RF) communication system to fulfil specific requirements. It involves the design of RF transceiver chains and the associated hardware (HW) components (digital-to-analogue converter (DAC)/analogue-to-digital converters (ADCs), filters, local oscillators, mixers, power amplifiers (PA), low-noise amplifier (LNA)), in addition to the design of antenna and their interface with one or multiple RF in form of beamforming architecture, multiple-input multi-output (MIMO) transmission, or carrier aggregation. The design begins with link analysis considering performance requirements (e.g., data rate, range), system parameter (e.g., transmission power, frequency range, bandwidth), channel characteristics (e.g., path loss, fading, interference), HW non-idealities (e.g., PA output power, noise figure (NF), PN, ADC resolution), and signal processing margins (e.g., waveform impact on PA, equalization and detection performance). Moreover, other constraints can be used in the optimization, such as size, cost, energy efficiency, and flexibility.

The design also involves the radio access network that includes, but is not limited to, physical layer design such as the waveform, the modulation scheme design, design of multiple access protocols, radio resource management/allocation algorithms, etc.

Holistic radio design considers the entire radio system as a whole, including the hardware, software, and system-level components. It considers the interdependencies between different elements of the system, such as the radio hardware, signal processing algorithms, and network protocols, to achieve optimal performance, efficiency, reliability, and sustainability. It considers the overall system requirements and constraints, including, power consumption, form factor, cost, and scalability, in addition to the traditional radio design considerations such as frequency band, modulation scheme, and signal-to-noise ratio (SNR). The radio hardware and software are designed together to optimize the performance and efficiency of the system.

E2E radio performance in the context of WP4 refers to the overall performance of the radio link at the physical layer (PHY) from the transmitter to the receiver. This performance considers the impact of signal transmission (e.g., modulation and coding) and reception (e.g., equalization and decoding) techniques, HW components for digital signal processor (DSP) and RF, and subsystems (e.g., relay, gateway, fronthaul) in between. The E2E radio performance contributes to the overall E2E system performance, which comprises one or multiple radio links, and needs to consider the impacts of other components at higher layers of the communication network. E2E radio optimization framework is needed for the selection and integration of various subsystems and components to fulfil the performance requirements, with a minimal cost and considering the constraints in each subsystem. Different cost measures can be incorporated in the optimization, such as the amount of HW resources (antennas, number of base stations, processing power), and operational cost (e.g., energy consumption). The optimization framework involves 1) component models and simulation tools to evaluate the performance under different scenarios and parameters, and 2) optimization tools to select the best settings of the design parameters. Optimization is required in the radio design stage to optimize the system, and it is needed in the operation to adapt the transmission schemes.

Performance analysis aims at the evaluation of the effectiveness and efficiency of a radio communication system in transmitting and receiving information. This includes measuring and comparing various performance metrics such as signal quality (measured by SNR or signal-to-interference and noise ratio (SINR)), signal strength (in relation to transmit power and receiver sensitivity), interference (because of HW non-idealities), noise (in relation to noise figure), latency, data rate, and reliability. Note that, while signal quality reflects the impact of signal strength, noise and interference on the theoretical achievable reliable data rate, considering individual parameter is relevant to HW performance assessment. Moreover, spectral efficiency can be considered for system analysis, especially for the radio design of base station. The results of the analysis are used to obtain design decisions, optimize system parameters, and improve overall performance.

2.1 6G radio design performance requirements

Performance requirements refer to the key specifications and characteristics that need to be met or exceed to ensure satisfactory operation, communication quality, sensing accuracy, and user experience. These air interface communication requirements include data rate (peak data rate, experience data rate, capacity), latency, coverage (range and angles), and reliability in terms of bit error rate (BER)/frame error rate (FER), and radio sensing related metrics. Note that value requirements, such as energy efficiency are discussed in Section 2.2.

2.1.1 Air interface communication requirements

This section introduces definitions of communication requirements from the perspective of air interface, and presents corresponding metrics for measuring the performance. The relation to communication service KPIs is provided in Section 2.3.3.

2.1.1.1 Data rate

It refers to the speed at which the information is successfully exchanged through the channel. The maximum theoretical data rate is the one that can be achieved under ideal conditions and depends on the waveform design and its respective numerology, modulation and coding schemes, bandwidth, and spatial multiplexing. It can be defined in terms of the number of bits transmitted per unit of time (bitrate), symbols (baud rate) or packets (packet rate). Different metrics can be used to assess the data rate performance at the air interface:

Throughput: refers to the overall effective transmission rate, considering several factors such as protocol overhead, retransmissions or network congestion.

Peak data rate: is the maximum data rate that can be achieved over a certain period of time. Since it does not consider limitations that might affect the communication performance, it is not sustainable for long periods of time.

Packet rate: corresponds to the number of packets transmitted correctly per unit of time. It is typically measured in packets per second and depends on the average packet size.

Capacity: for a given channel is the maximum data rate that can be transmitted over the channel with asymptotically small error probability, assuming no constraints on delay or complexity of the encoder or decoder.

Spectral efficiency: spectral efficiency indicates the information rate over a given bandwidth. It quantifies the amount of data that can be transmitted per unit of frequency bandwidth. It is measured in bits per second per Hertz (bit/s/Hz).

Sum rate: refers to the total data rate achieved in a communication system. It is the summation of the achievable rates of multiple concurrent transmissions, for example, different users that are multiplexed.

Average rate: average rate indicates the average amount of data transmitted per unit of time. It considers variations in the data rate over time, in contrast to peak data rates.

2.1.1.2 Coverage

Coverage is defined as the area where the signal can be received with acceptable quality and reliability. It can be quantified by various metrics, including

Range (spatial separation distance): denotes the maximum distance between a transmitter and a receiver up to which the signal can be successfully received, and the information is decoded for a specific modulation and coding scheme. For radio design, this indicates the distance at which a certain data rate can be achieved. Note that, the range is defined without a specific consideration of the channel type. For instance, in multipath propagation with uncorrelated paths (including line-of-sight (LoS)), the range can be shorter than if the channel consists of LoS only.

Beamwidth: is relevant when using directive antennas antenna, where the beamwidth defines the angle range over which the antenna transmits or receives most of its power.

Separation distance: refers to the physical distance between transmitter and receiver. The separation distance influences important factors such as the signal strength at the receiver and the performance of the system

SNR: Signal-to-noise ratio is defined as the ratio of the power of the desired signal to the power of the noise. It quantitatively measures the quality of a desired signal relative to the level of noise present in the communication system.

Coverage probability: represents the probability of achieving a certain level of performance. It can be measured in terms of a minimum SNR required for successful communication.

Outage probability: is a metric that quantifies the probability that the performance falls below an acceptable level and thus, the criteria required to maintain the communication are not met.

2.1.1.3 Air interface latency

Time it takes to transfer a given piece of information from a source to a destination, measured at the communication interface, from the moment it is generated by the source to the moment it is successfully received at the destination. In the context of air interface latency, it measures the time needed to transmit and receive L2 packet successfully. This includes processing delay, propagation delay, PHY frame alignment, and retransmission.

2.1.1.4 Air interface reliability

Air interface reliability refers to the consistency and robustness of a wireless communication link to maintain and sustain a high-quality connection without interruptions or significant degradation, especially in the presence of interference, noise, and other environmental or system disturbances. It can be measured by

BER: defines the ratio between the correctly received bits to the total transmitted bits. It is measured with respect to information bits at the channel coding interfaces (coded BER). The BER measured at the input of digital modulation is referred to as uncoded BER.

FER: measured at PHY, is the ration of correctly received L2 of frames to the total number of transmitted frames in a single transmission. With retransmission is considered, the FER at L2 can be improved.

BLER: block error rate (BLER) is more general than FER as it measures the ratio of correctly received blocks to the number of transmitted blocks. A block can be defined in various ways, such as the number of bits in one codeword or the number of bits in a modulation symbol such as OFDM.

SER: symbol error rate (SER) used for conventional digital modulation techniques, such as quadrature amplitude modulation (QAM). It quantifies the number of correctly demodulated symbols to the total number transmitted symbols.

NMSE: normalized mean square error (NMSE) provides a quality measure by quantifying the deviation of received symbols from the transmitted ones.

2.1.1.5 Implementation and operation

Besides fulfilling the communication KPIs, radio design needs to be optimized for implementation and operation. Relevant metrics include:

Complexity: is related to the challenges of hardware design and manufacturing, in addition to signal processing computational complexity of modulation and coding schemes, synchronization, channel estimation, equalization.

Cost: in relation to PHY, this refers to the financial expenses associated with various processes in the design, implementation, and deployment, as well as, the expense of materials.

Energy efficiency: is related to the ability of minimizing the energy consumption of the radio system while achieving specific communication requirements.

Table 1 presents the radio enablers for communication which are discussed in the following chapters and the mapping to the relevant KPIs. These evaluation results for these enablers with respect to the specified KPIs will be presented in the upcoming deliverables.

Table 1 The mapping of radio enablers proposed in this document for communication and relevant KPIs.

Air interface KPI	**Technical enabler (Section)**
Throughput	Link modelling of 6G physical layer (4.2.1), AI/ML-based PA non-linearity compensation (6.2.1), AI/ML-based CSI prediction (6.2.2.1), AI/ML-based beamforming (6.1.1.1), Learn RIS RM (7.3.4), Learned MIMO waveforms (6.3.1), AI-based MU-MIMO pairing (6.1.1.3), D-MIMO resource allocation (6.1.1.4), AI-enabled CSI compression (6.3.2.2), Scalable transmission (7.1.3), Sub-THz D-MIMO assisted with sub 6 GHz measurements (7.2.1.1), TN-NTN spectrum coexistence and sharing frameworks (8.1.2).
Capacity	AI-based MU-MIMO user pairing (6.1.1.3), TN-NTN spectrum coexistence and sharing frameworks (8.1.2), Risk-informed random access (8.2.2), Sub-THz access methods (8.2.1), Risk-informed random access (8.2.2).
Coverage	Coverage analysis at THz frequencies (300 GHz-3 THz) (4.1.2), Channel models at Sub-THz frequencies (4.1.1), RIS control procedure, interface, integration (7.3.1), Inclusive radio interface via TN/NTN enhancements (3.2), Hardware modelling of RIS (4.2.2), D-MIMO resource allocation (6.1.1.4) sub-THz D-MIMO assisted by a sub-6 GHz macro network (7.2.1.1), NTN-aided localisation (9.1.1), Integrated communication and monostatic sensing (9.1.2), Multi-static sensing (9.1.4).
Air interface latency	AI/ML-based beamforming (6.1.1.1), TN-NTN spectrum coexistence and sharing frameworks (8.1.2), Multi-RAT spectrum sharing (8.1.3), sub-THz access methods (8.2.1), risk-informed random access (8.2.2), Flexible baseband transceiver for JCAS (9.2.1), Resource allocation in multiband hybrid-beamforming transceiver (9.2.4).
BER	Link modelling of 6G physical layer (4.2.1), Polar constellations (5.3), AI-empowered PA non-linearity compensation (6.2.1), Optimized coded modulation (6.1.3), AI-based CSI feedback (6.3.2.1), Coherent joint transmission (7.1.1), Multi-antenna Location-dependent coded caching (7.1.8), Learn RIS RM (7.3.4), Waveform learning for JCAS (9.2.2).
BLER	Link modelling of 6G physical layer (4.2.1), AI-empowered PA non-linearity compensation (6.2.1), AI-enabled CSI prediction (6.2.2.1), Learned MIMO waveforms (6.3.1) Energy efficient LDPC channel encoding/decoding schemes (6.3.3), Flexible baseband transceiver for JCAS (9.2.1).
Complexity, energy efficiency	Gearbox PHY (3.1.1), Optimization framework for gearbox PHY switching (3.3.1), E2E optimization framework for energy efficiency (3.3.2), Zero-crossing modulation enabling energy-efficient 1-bit quantization (5.4), AI-empowered PA non-linearity compensation (6.2.1), Antenna muting (6.1.1.2), D-MIMO resource allocation (6.1.1.4), optimized coded modulation (6.1.3), Energy efficient coding (6.3.3), AI-enabled MU-MIMO optimization (6.3.4), Scalable transmission (7.1.3), Fully digital mMIMO with low resolution converters (7.2.2), Fully digital mMIMO with low resolution converters (7.2.2), D-MIMO assisted with RIS (7.3.2), TN-NTN spectrum coexistence and sharing frameworks (8.1.2), Multi-RAT spectrum sharing (8.1.3), Integrated communication and monostatic sensing (9.1.2), Resource allocation in multiband hybrid-beamforming transceiver (9.2.4), Resource allocation and protocols for inter-UE sensing (9.2.6), Power consumption of JCAS (9.2.7).

Spectral efficiency	Link modelling of 6G physical layer (4.2.1), Mainstream 6G waveforms at sub-THz frequencies (5.1), Zero-crossing modulation (5.2), ML-based beamforming with imperfect CSI estimates (6.1.1.1), AI-based MU-MIMO user pairing (6.1.1.3), AI-empowered PA non-linearity compensation (6.2.1), AI-based CSI feedback (6.3.2.1), AI-enabled MU-MIMO optimization (6.3.4), Fully digital mMIMO with low resolution converters (7.2.2), MRSS (8.1.3), Learned MIMO waveforms (6.3.1) , D-MIMO assisted with RIS (7.3.2).
Backhaul rate	RIS-assisted IAB (7.1.5).
Service coverage probability	RIS-assisted IAB (7.1.5).
FER	Optimized coded modulation (6.1.3).
Sum rate	Decentralized transmission (7.1.6), One-bit ADC transmission (7.1.7), Coded caching (7.1.8).
Average rate	Decentralized transmission (7.1.6).
SER	One-bit ADC transmission (7.1.7).
Cost	Fully digital mMIMO with low resolution converters (7.2.2), Zero-crossing modulation enabling energy-efficient 1-bit quantization (5.4).
Outage probability	Distributed massive MIMO (7.1.4), D-MIMO assisted with RIS (7.3.2).
NMSE	RIS channel estimation (7.3.3).
Spatial separation distance	Assumptions and models to determine sharing possibilities (8.1.1).

2.1.2 Radio sensing requirements

This section introduces definitions of radio sensing requirements related to PHY. The relation to the sensing/localization service KPIs is provided in Section 2.3.3.

2.1.2.1 Location/sensing accuracy

The location accuracy (units: meters) is location error norm value corresponding to a certain percentile (e.g., 90%, 99%) of the location error norm.

The error norm is the distance between the true and estimated location and can be measured 3D (XYZ) or two-dimensional (2D) (XY) coordinates.

The location accuracy can be computed for both connected devices and passive objects. In the latter case, it could be referred to as the sensing accuracy.

2.1.2.2 Sensing latency

The latency (units: seconds) is the time between initialization of sensing/localisation procedure and acquiring localisation/sensing estimate.

2.1.2.3 Orientation accuracy

The orientation accuracy (units: degrees) is the orientation error norm value corresponding to a certain percentile (e.g., 90%, 99%) of the orientation error norm. The error norm is the distance between the true and estimated orientation, determined as the distance between rotation matrices or quaternions, via the Rodrigues formula.

2.1.2.4 Location coverage

The location coverage (units: square or cubic meter or %) is the area or volume or fraction of a space in which the localisation error is below a certain limit.

2.1.2.5 Sensing resolution

The sensing resolution (units: meter or radians, or meter/second) is the smallest difference in position (or more generally in some dimension, e.g., range, angle, Doppler) between objects to have measurably different position (or range, angle, Doppler).

2.1.2.6 Sensing detection probability

The sensing detection probability is the probability that a target is detected given that it is present (i.e., there is a target, and the detection is successful).

2.1.2.7 Complexity, energy efficiency

Efficiency in sensing refers to the ability of a sensing system or device to perform accurate sensing while minimizing energy consumption. This encompasses not only the energy and power consumed during the sensing operation but also the energy consumed in processing and transmitting the sensed data, as well as communication.

To quantify efficiency in sensing, two key metrics will be considered:

Energy Efficiency Ratio (EER) is defined as the ratio between the output power (expressed in Watts, W), and the total power consumed by the sensing or communication system to achieve this power output. This parameter can be estimated at the transmitter and receiver of the system.

Consumption Factor (CF): is defined as a ratio between a specific performance achieved after a period of time "A" (application-dependent unit), and energy consumed for this period of time W (Joule unit). For communication, specific performance A can be the number of bits transferred. While for sensing, positioning, and ISAC, A can be detection probability, ranging accuracy, angle estimation accuracy, correct classification rate, radar mutual information, etc. "A" could also represent a function reliant on a condition, for instance, A = 0 when the accuracy fails to meet the specified requirement, and A = 1 when the accuracy fulfils the requirement.

Complexity: refers mainly to system and algorithm complexity in the JCAS context. System complexity refers to a system which is composed of many components which may interact with each other. Complex systems are systems whose behaviour is intrinsically difficult to model due to the dependencies, competitions, relationships, or other types of interactions between their parts or between a given system and its environment. Algorithm complexity refers to the amount of resources the algorithm needs to solve a particular problem, measured in terms of time or memory. A complex algorithm needs a larger amount of resources than required to complete its operations.

Table 2 presents the radio enablers for sensing which are discussed in the following chapters and the mapping to the relevant KPIs. These evaluation results for these enablers with respect to the specified KPIs will be presented in the upcoming deliverables.

Table 2 The mapping of the radio enablers proposed in this document for sensing and relevant KPIs.

Radio sensing KPI	Technical enabler (Section)
Location accuracy	NTN-aided localisation (9.1.1), Integrated monostatic and bistatic sensing (9.1.3), Jammer localisation (9.3.3), 6D tracking in JCAS scenarios (9.2.5), Resource allocation and protocols for inter-UE sensing (9.2.6).
Location coverage	NTN-aided localisation (9.1.1), Jammer localisation (9.3.3).
Sensing accuracy and resolution	Integrated communication and monostatic sensing (9.1.2), Integrated monostatic and bistatic sensing (9.1.3), Multi-static sensing (9.1.4), Flexible baseband transceiver for JCAS (9.2.1), Waveform learning for JCAS (9.2.2), Optimization of OFDM-based bistatic sensing (9.2.3), Resource allocation in multiband hybrid-beamforming transceiver (9.2.4), Resource allocation and protocols for inter-UE sensing (9.2.6), Power consumption of JCAS (9.2.7).
Sensing detection probability	Integrated monostatic and bistatic sensing (9.1.3), Flexible baseband transceiver for JCAS (9.2.1), Waveform learning for JCAS (9.2.2), Power consumption of JCAS (9.2.7).
Latency	NTN-aided localisation (9.1.1), Jammer localisation (9.3.3).
Orientation accuracy	6D tracking in JCAS scenarios (9.2.5).
Complexity, energy efficiency	Flexible baseband transceiver for JCAS (9.2.1), Waveform learning for JCAS (9.2.2), Resource allocation in multiband hybrid-beamforming transceiver (9.2.4), Resource allocation and protocols for inter-UE sensing (9.2.6), Power consumption of JCAS (9.2.7).

2.2 6G radio design value requirements

Key values are desirable attributes that the system possesses such as sustainability, trustworthiness, inclusion, etc. A KVI is a measure of how much the 6G system conforms to the value. For example, energy efficiency, and material life-cycle assessment (LCA) are indicators of how sustainable a system is. Coverage and cost of ownership are indicators of inclusiveness. Other social and economic metrics include life expectancy, gross domestic product (GDP) growth, happiness index.

2.2.1 Inclusiveness

To ensure that 6G can be inclusive for all people across the world, it needs to be affordable and scalable, with a great coverage everywhere. One way to achieve an affordable and scalable 6G system is to make sure that the system is global, i.e., the same system is utilized worldwide, for example by global standards continuing to be the main driver of 6G [ITU-905]. In addition to global standards, it is also important that 6G has an architecture design that is manageable by reducing the number options (i.e., options without a real market potential). In other words, 6G standardisation should aim for a proper number of manageable interfaces with relevant business impact. Network equipment needs to be affordable to operators while providing coverage everywhere. Also, mobile devices need to be affordable and low-cost devices should be available where only basic functionality is needed (e.g., with sensors).

2.2.2 Trustworthiness

A trustworthy radio system is designed and operated to ensure reliable, secure, and ethical communication between different radio devices or networks. It includes the radio devices, infrastructure, protocols, and personnel involved in the communication process. It prioritizes the quality of service in terms of reliability and latency, and it follows ethical and professional standards for communication, such as confidentiality, privacy, and accuracy, and avoids unauthorized access or interference. The system is also designed to ensure the safety and well-being of its users and the communities it serves and maintain high standards of technical and operational quality to ensure reliable and secure communication.

2.2.2.1 Reliability

Reliability measured by the probability of the system to operate correctly and without errors in the presence of noise, interference and other disturbances. Reliability is a broad aspect that needs to be considered in all system components such as communication reliability as defined in Section 2.1.1.4, sensing reliability, e.g. in relation to location and orientation accuracy, defined in Section 2.1.2.

2.2.2.2 Security

Radio security refers to the measures taken to ensure the confidentiality, integrity, and availability of communication over radio networks. It involves protecting the radio communication system from unauthorized access, interception, modification, or disruption by using various security mechanisms such as encryption, authentication, access control, and intrusion detection, in addition to the resilience of the physical infrastructure.

2.2.2.3 Resilience

The resilience of a system denotes its robustness against adverse events, i.e., in case of hazards, the system should maintain essential functionalities, mitigate the threat, and recover as soon as possible. With respect to the mobile network, such adverse events comprise a multitude of causes, e.g., natural disasters, cyber-attacks, and jamming. Hence, the network has to be able to detect and identify such events in order to initiate appropriate reactions, as well as to be designed in such a way that there are certain levels of redundancies that can alleviate the disturbances.

2.2.2.4 Integrity

Integrity in radio communications system refers to the quality of the signal being transmitted and received without any alteration or interference. This ensures that the information sent through the radio system is accurate, reliable, and complete, and that it has not been compromised or distorted in any way during transmission. To ensure integrity, various error detection and correction mechanisms, cryptographic techniques, and protocol-level safeguards are employed in radio communication systems. A border scope of integrity encompasses the trustworthiness of the sender and receiver. Authentication mechanisms, such as digital signatures, certificates, and cryptographic techniques, are employed to verify the identities of the communicating parties.

2.2.3 Sustainability

Radio sustainability involves designing and implementing radio systems and operations that minimize negative impacts on the environment, support social equity and inclusion, and ensure financial viability and resilience. It includes considerations such as energy efficiency, waste reduction, community engagement, cultural diversity, and financial sustainability. The goal of radio sustainability is to ensure providing valuable services to communities without compromising the well-being of people or the planet.

2.2.3.1 Value-based radio design

An approach to sustainable design that prioritizes the values and needs of the end-users, as well as all the elements of the system that 6G and its end-users co-exist, and thereby incorporates them into the design process to create solutions that are effective and efficient.

2.2.3.2 Energy efficiency

Energy efficiency refers to the effective use of power resources for transmission with minimal energy consumption. It can be measured by the ratio of the useful information or data rate to the consumed power.

Improving the energy efficiency is particularly important for battery-powered devices, like smartphones and Internet-of-Things (IoT) devices, where energy conservation is a priority. Although it is arguable that energy efficiency of battery-powered device does not significantly contribute to sustainability, and rather to improving user experience, it is worth noting the material impact, as frequent recharging leads to reduced battery efficiency over time, requiring either battery replacement or device replacement earlier than expected.

2.2.3.3 Life cycle assessment of materials

LCA approach provides insights into the environmental impacts of materials used in radio system throughout its life stages, from raw material extraction to disposal or recycling. Radio design should aim at optimizing the design of devices and infrastructure to reduce the material consumption, incorporate sustainable materials, and extend device life by providing reprogrammable solution, and improving energy efficiency of battery-powered devices.

2.2.3.4 EMF exposure from 6G radio

To protect people from substantiated health effects due to very high level of exposure to RF EMFs, science-based RF EMF exposure limits up to 300 GHz are developed by the international commission on non-ionizing radiation protection (ICNIRP), formally recognized by the World Health Organization. The limits are based on reviews of all relevant scientific literature and have been set with large margins to protect from substantiated short-term and long-term health effects. The ICNIRP guidelines from 1998 [ICNIRP98] have been adopted in most countries and form the basis of both the Council Recommendation 1999/519/EC with recommended EMF limits for the general public [1999/519/EC] and of the EU Directive 2013/35/EU with EMF limits for workers [2013/35/EU]. In 2020, the ICNIRP published updated guidelines [ICNIRP20] considering the latest available scientific information and data. The limits in the new guidelines are to a large extent the same as those from 1998. The 2020 ICNIRP limits have already been adopted in several national regulations and the Council Recommendation as well as the EMF Directive are expected to be updated based on the new guidelines in the coming years. Radio equipment for 6G will need to comply with the same EMF requirements as previous generations of mobile technologies. To assess the conformity with the EMF related safety requirements of the radio equipment directive (RED), products shall comply with the relevant EMF standards, for example, the European Standard EN 50385 [EN50385]. This standard prescribes that base station products shall be evaluated in accordance with the international standard IEC 62232 [EN/IEC62232] to determine EMF compliance boundaries (exclusion zones) for general public and workers.

Table 3 The mapping of radio enablers proposed in this document and relevant KVIs.

KVI	**Technical enabler (section)**
Inclusiveness	Inclusive radio interface via TN/NTN enhancements (3.2), Coverage analysis at THz frequencies (4.1.2), TN-NTN spectrum coexistence and sharing frameworks (8.1.2), Multi-RAT spectrum sharing (8.1.3), Sub-THz access methods (8.2.1), Risk-informed random access (8.2.2), NTN-aided localisation(9.1.1), Multi-static sensing (9.1.4), Flexible baseband transceiver for JCAS (9.2.1), Resource allocation in multiband hybrid-beamforming transceiver (9.2.4).
Trustworthiness	PHY security (3.4.1), Jamming resilience schemes (3.4.2), Learned MIMO waveforms (6.3.1), AI-based CSI feedback (6.4), RIS-assisted integrated access and backhaul (7.1.5), Signal level analysis for RIS (7.3.1.1), TN-NTN spectrum coexistence and sharing frameworks (8.1.2), Multi-RAT spectrum sharing (8.1.3), Sub-THz access methods (8.2.1), Risk-informed random access (8.2.2), NTN-aided localisation (9.1.1), Integrated communication and monostatic sensing (9.1.2), Integrated monostatic and bistatic sensing (9.1.3), Multi-static sensing (9.1.4, Waveform learning for JCAS (9.2.2), Optimization of OFDM-based bistatic sensing (9.2.3), Resource allocation and protocols for inter-UE sensing (9.2.6), UE-related security aspects of JCAS (9.3.2), Jammer localisation (9.3.3).

Sustainability	Gearbox PHY (3.1.1), Zero-crossing modulation (5.2), Learned MIMO waveforms (6.3.1), TN-NTN spectrum coexistence and sharing frameworks (8.1.2), Multi-RAT spectrum sharing (8.1.3), Sub-THz access methods (8.2.1), Risk-informed random access (8.2.2), NTN-aided localisation (9.1.1), Integrated communication and monostatic sensing (9.1.2), Multi-static sensing (9.1.4), Flexible baseband transceiver for JCAS (9.2.1), Waveform learning for JCAS (9.2.2), Optimization of OFDM-based bistatic sensing (9.2.3), Resource allocation in multiband hybrid-beamforming transceiver (9.2.4), 6D tracking in JCAS scenarios (9.2.5), Power consumption of JCAS (9.2.7).

2.3 Representative 6G use cases

6G use cases are outlined from a broad application perspective. Several use cases require communications and sensing services, which will be provided by the 6G network. The requirements are defined in the context of E2E service performance, which involves various network nodes. RAN plays a vital role as one of the system components that influence this holistic performance. The E2E requirements poses specific requirements on the radio design. In particular, the data rate at the air interface should consider protocol overhead across multiple layers. Consequently, this rate should exceed the throughput observed at the application layer. Air interface contributes to the overall E2E latency, and thus, it should be minimized to compensate for latency present in other layers. Moreover, the communication service reliability is influenced by the reliability and coverage of the wireless links. Furthermore, service availability is impacted by coverage, which is related to the link range and environment characteristics. Importing sensing into radio design introduces extra requirements and constraints, including required bandwidth for ranging resolution and number of antennas for angular resolution.

The variety of requirements on communication and sensing can be used to optimize the radio design with respect to KVI targets. Ideally, a radio design tailored to a single use case would lead to the best optimized solution. However, to incorporate flexibility into the system design, it is beneficial to define a limited number of scenarios that are suitable for a wide range of use cases. These scenarios can be defined with a radio design that specifically aims to meet the most stringent requirements. Such a design should also maintain flexibility for further optimization during the operation. Accordingly, the objective of this section is to describe radio-specific scenarios that represent groups of use cases, focusing on extreme requirements, as illustrated in Figure 2-1. Selected use cases are analysed based on their service requirements. The service requirements are mapped to the related radio requirements. Based on extreme radio requirements, exemplary radio scenarios are defined that fulfil an extreme requirement in one dimension while only support relaxed requirements in other dimensions.

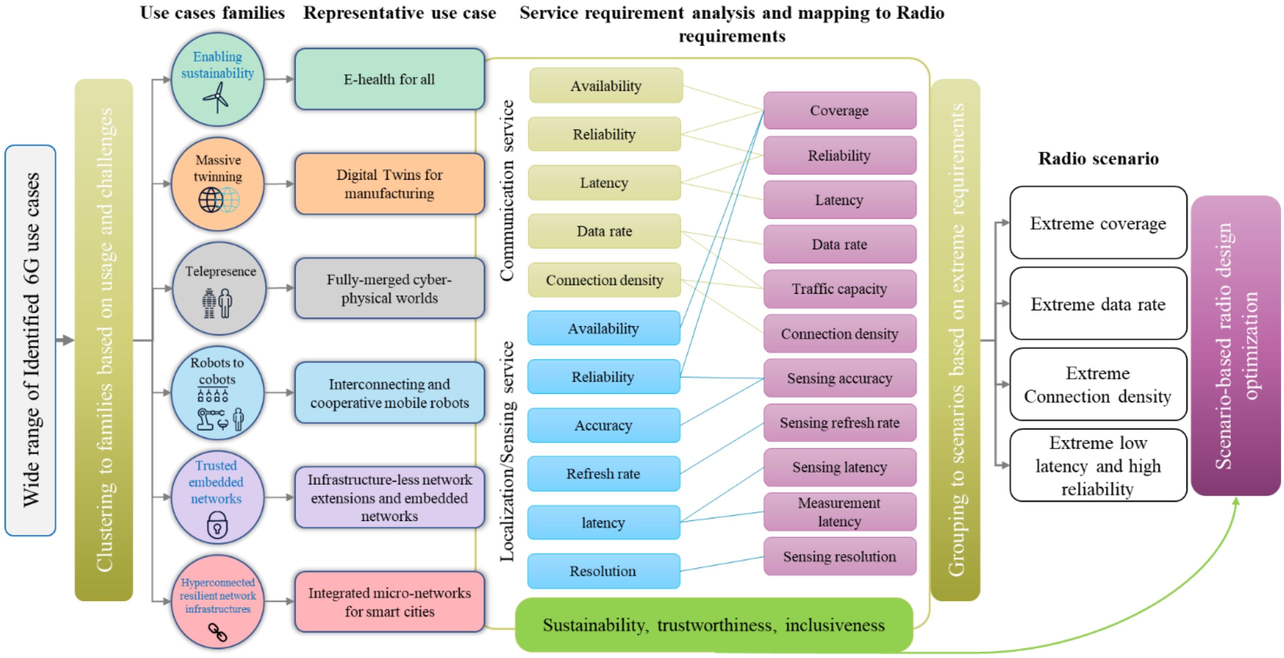

Figure 2-1 Methodology of defining radio scenarios based on use cases.

2.3.1 Overview of Hexa-X 6G use cases

Hexa-X has introduced a set of use cases via the combination of a top-down approach driven by vision, the core values and research challenges, and a bottom-up approach to illustrate the use of new technologies. The set of use cases has been clustered into six families that describe use cases involving similar interactions and answering one or several of the six research challenges: connecting intelligence, network of networks, sustainability, global service coverage, extreme experience, and trustworthiness [HEX21-D12, HEX22-D13]. The initial use cases of Hexa-X-II are based on Hexa-X use cases, and are selected to represent three categories: sustainability driven, vertical motivated by business and industry, and technology-centric on novel and challenging technical solutions [HEX223-D11]. WP4 aims at defining scenarios based on selected use cases that cover most technical aspects of communication and sensing services, relying on the definitions of these use cases in [HEX22-D13].

The Hexa-X use case families are:

1. Enabling sustainability: the use cases in this family address different aspects of sustainability, such as more efficient usage of resources, protection of the environment or inclusion to provide access to crucial services everywhere, even in remote areas, potentially with support of NTN. As a representative, WP4 considers “**E-health for all**” (Hexa-X-II sustainability category).
2. Massive twinning: involves massive use of digital twins to represent, interact and control actions in the physical world. The use cases therein require transferring vast information volumes, low delays, high reliability, and capacity levels that will be pushing the current boundaries. High-resolution and interactive 4D mapping is needed. In WP4, “**Digital twins for manufacturing**” (Hexa-X-II vertical category) will be used to represent this family.
3. Telepresence: covers immersive telepresence for enhanced interactions, involving mixed reality or merged reality, providing extreme and fully immersive experience. Extreme experience is needed to be able to meet the needed data rates. Low enough latency with high data rates and enough reliability is needed to avoid incomplete experience or even nausea. As an example, “**Fully-merged cyber-physical worlds**” and **"merged reality game/work"** (Hexa-X-II technology-centric category) will be in focus of WP4.
4. Robots to cobots: includes various use cases involving interacting robots, at home to facilitate everyday life, as well as in professional environments to improve the efficiency of processes. Some use cases, for example in the industrial context, demand extreme performance, in terms of latency,

reliability, and positioning. The use case, **“Interconnecting and cooperative mobile robots”** (Hexa-X-II technology-centric category) is analysed in WP4 for this family.

5. Trusted embedded networks: this family gathers the use cases involving subnetworks, or networks of networks, requiring a high-level of trustworthiness. Among the use cases, “**Infrastructure-less network extensions and embedded networks”**, will be considered in WP4.
6. Hyperconnected resilient network infrastructures: it groups the use cases involving subnetworks, or networks of networks, requiring a high-level of resilience. As an example, **“integrated micro-networks for smart cities”**, which is combined with “**Immersive smart cities use case”**.

Other projects such as NGMN has presented another classification of use case [NGMN-UC22], which were provided by members representing network operator, technology suppliers, and academic institution, in four generic classes:

1. *Enhanced human communication*: includes use cases families that focus in enhancing human communication, including extended reality (XR) immersive holographic telepresence communication, multi-modal communication for teleoperation, and intelligent interaction by sharing of sensation, skills, thoughts.
2. *Enhanced machine communication:* encompasses use case with robot network fabric, and interacting cobots.
3. *Enabling services:* includes use cases that require new services for accurate positioning, localization and tracking, interactive mapping, digital twins and virtual worlds, automatic detection, protection and inspection, digital health, smart manufacturing, and trusted composition of services
4. *Network evolution:* collects use cases related to the evolution of technology, including, Trusted native AI as a service, energy efficiency, and coverage expansion.

2.3.2 Use cases specifications and relation to radio

Use cases description includes parameters related to the operation conditions [HEX22-D13]: type of environment, mobility, connection density, type of end-devices, and service requirements. Based on that, initial technical requirements can be devised on the type of deployment, radio devices, and frequency band. These requirements impact the radio design at different stages. In Figure 2-2, an abstracted view of the impact on radio link in form of abstracted channels is provided.

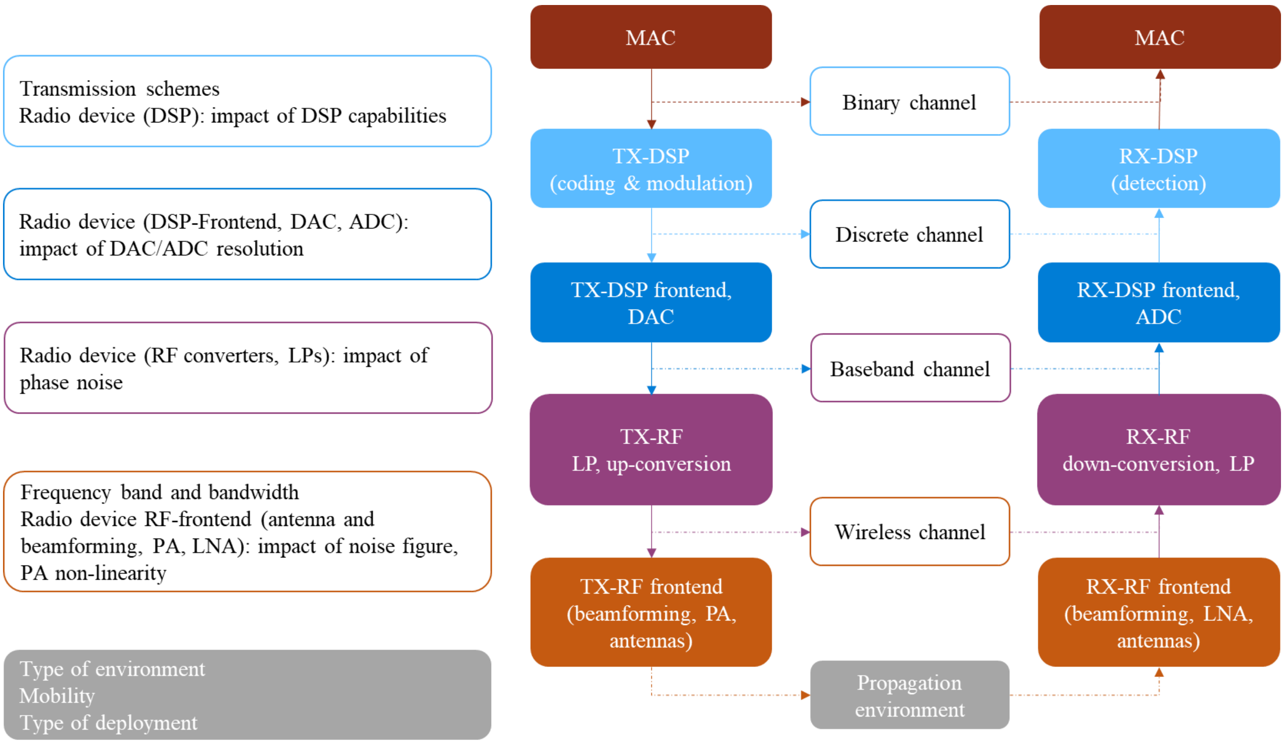

Figure 2-2 Impact of use case scenarios on radio design.

- Propagation environment: considers physical environment effects on the signal, including obstacles, reflectors, atmospheric effects, etc. It is influenced by the environment, deployment type, and mobility.
- Wireless channel: abstracts the effects of RF frontend of radio device in addition to the propagation channel. This depends on the frequency band, and bandwidth, in addition to the nonlinearities of device components: antenna, beamforming, PA, and LNA.
- Baseband channel: it considers the effects of radio device frequency convertors on top of the wireless channel.
- Discrete channel: includes on top of the baseband channel the effect of device DAC and ADC resolution and the DSP-fronted filtering and pre-processing capabilities.
- Binary channel: this channel is the highest level of abstraction, and it provides a relation between the decoded data and input data, where link performance can be evaluated. This channel is directly impacted by the capabilities of DSP in terms of hardware and algorithms.

The holistic E2E radio design in terms of HW and transmission schemes needs to be aware of the inputs related to the use case description.

By analysing the selected use cases, the following parameters are identified:

Type of environment: it can be classified to (indoor, outdoor), (urban, suburban, rural), (private, public), (controlled, uncontrolled, semi-controlled), (fixed, mobile), (ground, high-rise). Several combinations are possible to create a relevant environment. For instance, controlled indoor representing factory hall, shop floor, and warehouse, where variables affecting wireless signal propagation, interference, and operation are regulated or managed. Semi-controlled indoor corresponds to education institution, health centres. Public indoor describes facilities such as malls, subways. Outdoor environment can be urban to describe dense users in cities and streets, suburban with less density, and rural for sparse user density, as in countryside, forests, and mountains. High-rise environment represents, e.g., high buildings.

Mobility: can be classified as static, low mobility (walking speed), medium mobility (<10 m/s), high mobility (typical speed of cars), very-high mobility (high-speed train), and ultra-high mobility (for airplanes/ low-earth orbit (LEO) satellites). Mobility can be controlled, where the trajectory and speed are known, as in the case of autonomous vehicles. Furthermore, mobility can be in 2D area or in 3D space, as in the case of UAV.

Connection density: total number of connected and/or accessible devices per unit area or volume (3D deployment).

Type of devices: devices can be classified as (user devices, infrastructure devices). User devices can be categorized according to the usage to handheld (e.g., laptops, tablet, smartphones), wearable (body sensors, smartwatch, tactile gloves), industrial (sensors, alarms, robots, AGVs), medical (blood pressure monitor, insulin pumps). Infrastructure devices include, base station, gateway, relays, access points, RIS. The type of device might pose constraints on the design of radio devices.

Type of deployment: deployment can be classified to (cellular, cell free, D2D), (local are, wide area), (static infrastructure, mobile infrastructure), (long range, short, range), (fixed, temporary), (private, public). Combination of different deployment can be realized in the form of network of network, e.g., local area networks connected to wide area network. Cellar deployment with specific range results in different cell types, including small-cell, macro-cell, microcell. The deployment of cells can be dense or sparse. Local area networks can be at the level of distributed sensor network, embedded networks in devices, or body area network. Wide area deployment can be realized by terrestrial and non-terrestrial infrastructure.

Frequency bands: several frequency bands can be used for different purposes. Lower bands (sub-1 GHz and sub-6 GHz) are suitable for providing wide coverage for communication and sensing, whereas high bands (mmWave, and sub-THz (100-300 GHz)) offers wide bandwidth for data intensive communication and accurate sensing in a shorter range. As a trade-off, cmWave (7-15 GHz) offers wide bandwidth and good coverage to accommodate both communication and sensing. Additionally, satellite bands (e.g., S-band (2-4 GHz) or Ka band (26-40 GHz)) are suitable for providing wide coverage when combined with appropriate constellation deployments. Frequency bands can be licensed and unlicensed or dedicated private bands. A combination of different bands can be used in the deployment of use cases. Also see Section 2.4.

Communication service requirements: which are derived based on the application specification of the use case, and they are defined in the context of E2E in [HEX22-D13]. The corresponding air interface requirements are discussed in Section 2.1.1. The communication service requirements are:

- Availability: percentage of time during which quality of service (QoS) targets are met and a specific service is offered during operation. Additional information on the resilience of the application, such as survival time [ms] or acceptable downtime of a service, should be included. Communication service availability is closely related but not limited to RAN **coverage**.
- Reliability: percentage of the amount of sent packets delivered within QoS constraints. To achieve the reliability requirements, the corresponding **air interface reliability** and RAN **coverage** should be considered.
- Latency: E2E latency for communication service between two application endpoints from use case perspective with allowed variability/Jitter and/or expected upper bound. One should distinguish between uplink (UL) and downlink (DL) and detail expected packet sizes and traffic characteristics in the deployment characteristics, if available, and access latency. This latency is affected by the **air interface latency and reliability**.
- Data rate: (minimum expected, maximum sustained, peak) [Mbit/s] is defined with respect to a single UE (minimum expected, maximum sustained) and a single base station (peak). Minimum expected data rate ensures correct operation of the use case (with reduced QoS or limited functionality). Maximum sustained data rate is the maximum a UE needs to be able to maintain continuously, and which is typically smaller than the peak data rate that a single base station supports which can schedule multiple UE in parallel. This is related to the RAN **user experienced data rate, peak data rate,** and **traffic capacity** to fulfil the demands of multiple UEs.

Localization and sensing service requirements: these requirements are defined at the application level, with specific focus on localization, considering radio-based sensing. More details on the definition of radio related KPIs are presented in Section 2.1.2.

- Availability: percentage of time during which location or sensing service requests are answered and the given QoS targets are fulfilled. This is influenced by RAN **coverage.**
- Reliability: percentage of requests that are fulfilled within the agreed QoS targets. It is impacted by the radio **sensing accuracy** and **coverage**.
- Latency: maximum tolerable service latency from the request being issued by the consumer (application, service) until location/sensing response being provided. It is impacted by radio **measurement latency** to collect all required data and **sensing accuracy** of different parameters.
- Refresh rate: the rate at which new information (e.g., location estimates) need to be obtained by the application. It is influenced by radio **sensing refresh rate** that depends on the architecture and waveforms.
- Location accuracy: accuracy of the estimated location reported in horizontal and vertical position accuracy. It is influenced by the **sensing accuracy** of involved parameters, such as delay.
- Orientation accuracy: accuracy of the estimated direction of UE: roll, pitch, yaw. It is influenced by the **sensing accuracy** of involved parameters, such as angles.
- Resolution (range/angular/velocity): required minimum distinguishable (range/angular/velocity) between two objects. It is influenced by the **sensing resolution** of involved parameters (delay, angles, Doppler).

Sustainability and trustworthiness: are required to be considered in all use cases. Value requirements, such as sustainability, trustworthiness, and inclusiveness, can be exemplified by attributes like energy efficiency, physical layer security/privacy, and cost. These can either form the 'objective' or 'constraint' in radio system design. The decision to categorize them as either objectives or constraints depends on the specific value requirement and possibly other factors. For instance, aspects like privacy and security should ideally be set as constraints. Within those constraints the system design can focus on achieving maximum performance, such as throughput. In such cases, making privacy a primary objective might not be appropriate. Conversely, other values like sustainability offer more flexibility. Energy efficiency, representing sustainability, can either be the primary objective or a constraint. For example, one could design a system that minimizes energy consumption while still maintaining a specified level of link quality. Alternatively, with a defined energy budget as a constraint, the system can aim to maximize performance metrics like throughput. Further consideration of the role of KVIs in defining radio scenarios will be investigated during the course of the project.

2.3.3 Service KPIs ranges

Based on analysing the KPIs tables of the selected use cases in Section 2.3.1, which are reported in HEX22-D13], different KPI ranges are identified. Table 4 summarizes the KPI ranges for communication service in addition to the connection destiny, and Table 5 summarizes different KPI ranges of localization and sensing.

Extreme values for communication are aligned with IMT-2030 capabilities [ITU-905]. In particular, for service extreme-reliability of (99.9999-99.999999%), an air interface reliability of $(1-10^{-5})$-$(1-10^{-7})$ without retransmission is required. Service with extreme-low latency (0.1-1 ms) is typically relevant to local deployment, where the air interface latency has the biggest impact. The ultra-high data rate (10-100 Gbit/s), corresponds to the highest data rate (peak data rate) envisioned by IMT-2030 and might only be applicable to base stations simultaneously serving multiple UEs, but not to an individual UE. Note that extreme-high data rate (> 100 Gbit/s) could be relevant to future use cases. In relation to connection density, IMT-2030 targets ultra-high density (10^{6}-10^{8} devices/km^2). Extreme-high connection density (> 10^8) might be relevant when considering volume density, where devices are distributed vertically and horizontally, such as in a multi-level building. IMT-2030 specifies a targeted positioning accuracy of (1-10 cm), which corresponds to high location accuracy. However, other ranges are relevant to specific use case.

Table 4 Communication service KPIs ranges and their relation to radio KPIs. Dark green highlights IMT-2030 targeted capabilities, whereas the light green represents IMT-2020 capabilities. Extreme requirements in blue are beyond the ranges of IMT-2030, but encountered in the selected use cases requirements in [D3.1].

Service KPI	Qualitive measure	Quantitive range	Radio related KPIs	Notes
Availability [%]	High	99-99.99	Coverage	Other air interface requirements should be fulfilled within the coverage area.
	Ultra-high	99.99-99.9999		
	Extreme-high	99.9999-99.999999		
Reliability [%]	High	99-99.99	Coverage	Radio coverage should be maintained to avoid lost packets
	Ultra-high	99.99-99.9999	Link Reliability	
	Extreme-high	99.9999-99.999999	(99.999-99.99999)	
Latency [ms]	Medium	50-100	Latency	Air interface reliability impacts service latency when retransmission is needed
	Low	10-50	Reliability	
	Ultra-low	1-10		
	Extreme-low	0.1-1		
Data rate [Gbit/s]	Low	0.001-0.01	Peak data rate (design parameter)	Traffic capacity influences infrastructure data rate requirements
	Medium	0.01-1	User experienced data rate (under realistic conditions)	
	High	1 - 10		
	Ultra-high	10 -100		
	Extreme-high	>100	Traffic capacity	
Connection density [devices/km^2]	Medium	10^{2}-10^{4}	Connection density	Connection density and
	High	10^{4}-10^{6}	Traffic capacity	traffic capacity influence deployment options
	Ultra-high	10^{6}-10^{8}		
	Extreme-high	> 10^8		

Table 5 Localization/sensing service KPIs ranges and their relation to radio KPIs. Dark green highlights IMT-2030 targeted capability for location accuracy. Other ranges are concluded from the requirements in [D3.1].

Service KPI	Qualitive measure	Quotative Range	Radio related KPIs	Notes
Availability [%]	High	99-99.99	Coverage	Other requirements should be fulfilled within the coverage area
	Ultra-high	99.99-99.9999		
Reliability [%]	High	99-99.99	Coverage	Sensing accuracy of individual parameters (range, angles)
	Ultra-high	99.99-99.9999	Sensing accuracy	
Latency [ms]	Medium	50-100	Measurement latency	It is impacted by the probing signal duration and sensing accuracy, and the latency of collecting distributed measurements.
	Low	10-50	Sensing accuracy	
	Ultra-low	1-10		
	Extreme-low	0.1-1		
Refresh rate [1/s]	Low	1/3600-1	Sensing refresh rate	This depends on the sensing architecture and waveform design
	Medium	1-10		
	High	10 - 20		
	Ultra-high	20 -10000		
Location accuracy [cm]	Medium	10-100	Sensing accuracy	Multiple measurements (e.g., range, angles) are needed for localization depending on the architecture.
	High	1-10		
	Ultra-high	0.1-1		
	Extreme-high	< 0.1		
Orientation accuracy [°]	Medium	5-10	Sensing accuracy	This deepens on the sensing architecture.
	High	1-5		
	Ultra-high	0.1-1		
	Extreme-high	< 0.1		
Range resolution [cm]	Medium	10-100	Sensing resolution	In particular delay resolution. Multiple measurements might be used.
	High	1-10		
	Ultra-high	0.1-1		
	Extreme-high	< 0.1		
Angular resolution [°]	Medium	5-10	Sensing resolution	In particular angular resolution. Multiple measurements might be used.
	High	1-5		
	Ultra-high	0.1-1		
	Extreme-high	< 0.1		
Velocity resolution [m/s]	Low	1-10	Sensing resolution	In particular doppler resolution.
	High	0.5-1		

2.3.4 Radio representative scenarios

By examining the KPIs of the individual selected use case, it is notable that each use case requires extreme requirements in one of the four dimensions: coverage, data rate, connection density, and (reliability and latency), while other requirements are variable and less stringent. Accordingly, four radio representative scenarios are defined considering extreme requirements. Ultra-high data rate is determined as one driver, resulting in a scenario focusing on **"extreme data rate"**, and it represents both the use case *Digital twins for manufacturing*. For use cases with low data rate, where reliability and low latency for communication and sensing are the main focus, a scenario for **"Extreme low latency and high reliability"** is defined. Examples of uses cases of this scenario are *interacting and cooperative mobile robots* and *infrastructure-less network extensions and embedded networks***.** For medium to high data rate (0.1-10 Gbit/s), where latency and reliability are relaxed, but connection density is the focus, a scenario for **"extreme connection density"** is recognized. This scenario corresponds to the use cases *fully merged cyber-physical worlds*, merged reality game/work, and *immersive smart cities*. Finally, inspired by the requirements of the use case *E-health for all*, a scenario for **"extreme coverage"** is defined**,** where the focus is on providing communication and localization services everywhere with variable requirements. Table 6 summarizes the ranges of KPI requirements for the different radio representative scenarios.

Table 6 Radio scenario requirements highlighting the extreme focus in dark green, with light grey showing other relaxed requirements.

Radio scenario	Data rate	Reliability	Latency	Connection density	Coverage	Sensing-related capabilities
(1) Extreme coverage	Low Medium	Variable	Variable	Variable	Ultra-wide Extreme-wide	Variable
(2) Extreme data rate	Ultra-high Extreme-high	Variable	Variable	Low Medium	Local	Variable
(3) Extreme connection density	Medium High	Variable	Variable	Ultra-high Extreme-high	Variable	Variable
(4) Extreme low latency and high reliability	Low	Ultra-high Extreme-high	Ultra-low Extreme-low	Variable	Local	Ultra-high

2.3.4.1 Representative scenarios definition

The scenario specifications cover environment types, deployment options, applicable radio devices, mobility, and frequency range. From these, several sub-scenarios can be derived by selecting a combination of different parameters.

Table 7 provides the relevant radio specifications for the described scenarios.

Extreme coverage: this scenario primarily aims to offer consistent service coverage everywhere, especially in sparsely populated areas. The objective is to deliver basic mobile broadband connectivity to sparsely populated areas, and basic data rate for remote areas, in addition to localization and sensing services for some use cases such as automotive. Enhanced enhanced Mobile Broadband (eMBB) and massive machine-type communications (mMTC) 5G UE devices can be employed for this purpose, along with new energy-neutral devices suitable for remote locations. Connection density ranges from low in rural areas to high in suburban areas. Various deployment options can be exploited to ensure coverage, considering all levels of mobility. Typically, lower frequency bands are preferred for cellular network and low-altitude coverage, whereas satellite bands are needed for integration with satellite communication. Multiple radio design options should be considered for different combination of connection density and data rate.

Extreme data rate: The focus of this scenario is to provide ultra-high or extreme peak data rate (>10 Gbit/s) within local, controlled, or semi-controlled environment. Data collected from local devices are routed through either an access point or gateway, which can be stationary or exhibit controlled, limited mobility. Potential deployments include small cells for local devices and D2D for relying to the access points. To achieve this data rate, high-frequency bands with ultra-wide bandwidths are essential, which requires new type of devices. In addition, factors like coverage range, angles, and connection density should be incorporated into the radio design. Multiple radio options can be optimized depending on the communication range and peak data rate requirements.

Extreme connection density: The objective here is on delivering medium to high data rates for high-connection density of users, while also accommodating variable latency and reliability QoS requirements. Coverage requirements can vary, potentially being limited to specific urban areas with high user connection density and ranging from static to medium mobility. Advanced devices are required for higher data rates, as well as to meet various reliability and latency specifications. Depending on user connection density, various cell size deployments might be needed. In addition to the techniques for improving spectral efficiency at lower frequency ranges, wide bandwidth at mmWave is relevant. This scenario does not necessarily require an entirely new radio design or device type and capabilities, but rather build upon 5G enhancement.

Extreme low latency and high reliability: This scenario is a refined extension of 5G enhanced ultra-reliable low-latency communications (eURLLC). It prioritizes achieving extreme levels of reliability and latency, necessitating new device types. The data rate remains low, and the coverage is local indoor or embedded network with static or low mobility. An essential aspect of this scenario is ultra-high sensing performance, in terms of accuracy, resolution, refresh rate, and latency. As a result, radio design should address the requirement of both communication and sensing services. Even though, the data rate is low and might be achieved using lower frequency bands, wideband at higher frequency bands can be utilized to reduce latency and fulfil stringent sensing requirements.

Table 7 Representative scenarios definition.

Radio scenario	Environment type	Deployment option	Radio devices	Mobility	Frequency
Extreme coverage	Mobile indoor Public indoor Outdoor (urban, suburban, rural),	Long range Short range Fixed/temporary Mobile infrastructure Integration of TN/NTN	Enhanced 5G (mMTC, eMBB) devices Energy neutral devices	Static Low Medium High Very-high Ultra-high	Sub-GHz Sub-6 GHz 7-15 GHz Satellite frequency ranges
Extreme data rate	Controlled and semi-controlled indoor and outdoor	Small cell D2D Sensor network with a gate way Embedded network	Access points for backhaul Gateway for sensors Local devices	Static Low mobility Controlled mobility	mmWave or sub-THz Mixed and unlicensed for local connections
Extreme connection density	Urban indoor/outdoor with high density of users High-rise	High density of cells Macro cell Micro cell	Reliable high data rate with bounded latency devices	Static Low Medium	mmWave 7-15 GHz high bandwidth
Extreme low latency and high reliability	Indoor Embedded network	Small cell On premises infrastructure Sensor network	High reliability & low latency devices	Static Low mobility Controlled mobility	Private frequency Sub-GHz Sub-6 GHz 7-15 GHz mmWave, sub-THz for sensing

2.3.5 Comparison with ITU usage scenarios

The idea of defining usage scenarios for use cases is presented by ITU [ITU-905]. Six usage scenarios have been defined:

1- *Immersive communication*, which is based on extended enhancement of eMBB in terms of data rate. It supports uses cases such as, immersive XR, holographic communication, and telepresence.
2- *Hyper reliable and low-latency communication*: it is an extension of eURLLC, and support use cases with more stringent requirements of reliability and latency, such as communication in industrial environment for full automation, control, and operation.
3- *Massive communication*: it is an extension to mMTC in terms of connection density. It is typical for use cases with massive number of connections, such as smart cities, logistics, and environment monitoring.
4- *Ubiquitous connectivity:* it aims to enhance connectivity to bridge the digital divide, by providing coverage and services to uncovered or scarcely covered areas.
5- *AI and communication:* targets support of distributed compute and AI for use cases such as assisted automated driving, offloading of heavy computation. From radio communication requirements, this scenario overlaps with immersive communication.

6- *Integrated sensing and communication*: this usage scenario facilitates new applications and services that require sensing capabilities, for localization, mapping, imaging and other applications. From a communication perspective, this scenario overlaps with the first four scenarios.

Table 8 illustrates a summary of the interrelation between various use case classification approaches and their relation to the defined scenarios. A mapping exists between the ITU usage scenarios and the proposed radio scenarios. This mapping is one-to-one for both extreme coverage and ubiquitous connectivity. The extreme data rate scenario overlaps with some use cases of immersive communication and encompasses the usage scenario of artificial intelligence and communication. The extreme connection density scenario aligns with massive communication and a subset of immersive communications use cases. The scenario emphasizing extreme low latency and high reliability corresponds directly to hyper-reliable and low-latency communication, in addition to including the usage scenario of integrated sensing and communication.

Table 8 summary of relation between different view of use cases and usage scenarios.

Radio scenario	Representative use case	HEXA-X use case family	HEXA-X-II category	ITU usage scenarios	NGMN classes
Extreme coverage	E-health for all	Enabling sustainability	Sustainability	Ubiquitous connectivity	Network evolution
					Enabling services
Extreme data rate	Digital twins for manufacturing	Massive twinning	Vertical	Artificial intelligence and communication	Enabling services
				Immersive communication	
Extreme connection density	Fully merged cyber-physical worlds and merged reality game/work	Telepresence	Technology	Immersive communication	Enhanced human communication
	Immersive smart cities & integrated micro-networks for smart cities	Massive twinning & Hyperconnected resilient network infrastructures	Vertical	Massive communication	Enabling services
Extreme low latency and high reliability	Interacting and cooperative mobile robots	Robots to cobots	Technology	Hyper reliable and low-latency communication	Enhanced machine communication
	Infrastructure-less network extensions and embedded networks	Trusted embedded networks	Technology, Vertical	Integrated sensing and communication	Enabling services

2.4 6G spectrum access requirements

According to a previous GSMA study [GSMA21], mobile operators needed between 80-100 MHz of contiguous mid-band spectrum to deploy 5G. Low-band spectrum is also needed for 5G coverage across urban, suburban and rural areas and to provide support for such services as the Internet of Things. It is an inescapable fact that 6G deployments will require large amounts of spectrum as well. The technical KPI requirements are determined based on specific use cases. One of the primary considerations is the type of spectrum access required, whether it needs to be dedicated or it can be shared.

There are also several trade-offs to consider, see Figure 2-3. The larger size of each trapezium means better coverage, more available bandwidth, and better positioning or sensing resolution. Higher frequency ranges often offer more bandwidth and are suitable for local deployments. On the other hand, lower frequency ranges provide better coverage. Licensed spectrum may provide deterministic latency, better reliability, and guaranteed quality of service. Bearing in mind that spectrum is an extremely valuable and strategic resource, it becomes evident that the ability to leverage existing 5G spectrum in an efficient and flexible manner is essential for a successful migration towards 6G, considering an evolution of eMBB in 6G. On the other hand, license-exempt access might be a suitable choice for some use cases, which also may reduce bureaucracy and cost.

Concrete requirements on spectrum access depend heavily on specific use cases (UC), as detailed in [HEX22-D13] and [HEX223-D11]; see also Section 2.3.1. For instance, relating to the radio scenarios in Table 6 of Section 2.3.4, the following requirements could be given:

(1) Extreme coverage: wide-area coverage including the support of NTN to achieve coverage in remote areas.
(2) Extreme data rate: local spectrum usage for subnetworks, potentially in homes or factories.
(3) Extreme connection density: simultaneous access to spectrum for a potentially massive number of interfering users; this scenario also addresses the overall amount of required spectrum, combining high data requirements with a high number of active users, like in the merged reality and gaming UC.
(4) Extreme low latency and high reliability: reliable access to spectrum, including mobility and initial access with low latency.

Additionally, since device and network usage can vary over time, dynamic spectrum usage for situation-aware device and network reconfigurations can enable a minimized environmental impact.

Finally, considering sensing related UC, specific requirements are given depending on the actual purpose. For instance, localization prefers higher frequencies because of the feasibility of smaller and more antennas and more available bandwidth for better angular and range resolution. Spectroscopy-like sensing, like in [Zuz09], may make use of nearly all frequency ranges. In fact, there are several spectral lines in higher frequency ranges that affect communication, but in turn provide sensing information, for instance on rainfalls.

It will be impossible to serve all the different use cases and derived requirements efficiently and sufficiently with a single frequency range, given the constraints and trade-offs briefly explained above. Demand is anticipated for both, a more efficient use of existing spectrum via sharing and improved coexistence, and for additional spectrum, considering a wide range from sub-1 GHz up to sub-THz frequencies [ITU-905]. [NGA23] gives a comprehensive overview on potential 6G spectrum bands from 1.3 GHz up to 275 GHz with current allocations from a North American perspective and the aim to achieve global consensus.

The need for flexible spectrum access including dynamic and shared use of spectrum is emphasized in [RSPG23-026], including sharing of spectrum between RAT generations as well as between TN and other types of networks like NTN or for temporarily and locally increased capacity demands. Further, to facilitate sustainability, [ITU-905] recommends the use of harmonised spectrum as much as possible, on both a global and regional level, to simplify equipment complexity and, hence, to improve affordability and digital inclusion.

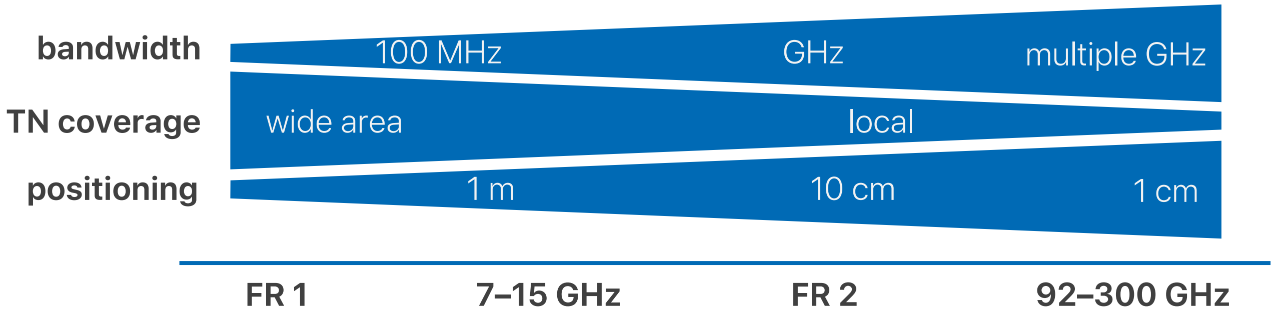

Figure 2-3 Frequency ranges under discussion for 6G and selected performance characteristics.

3 Radio design enablers for flexible, inclusive, sustainable and trustworthy radio

This chapter discusses radio design enablers that contribute to achieving the KVIs of 6G system. First, it presents enablers focusing on flexibility. These offer multiple radio configurations and resource management that can be adjusted based on operational needs. This flexibility aims at enhancing communication efficiency, by reducing the energy consumption and offering different capabilities that fulfil wide range of use case requirements. Next, considering inclusiveness, it introduces inclusive radio interface, which aims at ensuring connectivity everywhere by integrating both terrestrial and non-terrestrial networks, highlights the role of High-Altitude Platforms (HAP) in reaching remote areas. Subsequently, sustainable radio solutions are discussed with focus on improving the energy efficiency. These include techniques for optimizing the operation of flexible radio, and semantic communication for more efficient data transmission. Lastly, the chapter outlines enablers focused on physical layer security, and resilience schemes to ensure continuous communication, even in the face of disruptions like jamming.

3.1 Flexible radio design

A flexible radio interface provides multiple RF radio design options across different frequency bands with scalable bandwidth. It also offers multiple PHY options in terms of waveforms, modulation and coding. Such flexibility is granted at the design time without a need for hardware modifications or replacements. During the operation, the radio configuration is adapted to varying requirements, such as changes in frequency allocations or the need to support different types of services or applications. This helps in reducing operational cost while improving efficiency (e.g., energy) and scalability (e.g., bandwidth). The implementation follows software-defined radio (SDR) concepts, where the radio hardware can be programmed and reconfigured using software. This empowers a common hardware platform to support multiple communication standards and protocols.

3.1.1 Gearbox PHY

Conventional PHY designs primarily aim to increase spectral efficiency for a constrained bandwidth to achieve peak data rate. Such design increases the implementation cost of signal processing (high modulation order, advanced channel coding) and requires additional HW such as more RF chains for MIMO, and high-resolution ADC, which becomes the energy consumption bottleneck in the operation when the bandwidth increases. However, in practical scenarios, such high spectral efficiency is rarely needed, given non-uniform distribution of users over an area, varying activities at different time, and the dependency of coverage on the environment. Consequently, a range of spectral efficiency requirements emerge, which can be considered in the design of a flexible radio. This inspires the concept of gearbox PHY, which typically offers several predetermined radio options, denoted as gears. Each gear is optimized to provide a range of spectral efficiency. Specifically, the gear is designed with a particular RF hardware architecture, and adaptable modulation and coding schemes. The gearbox PHY approach allows practical implementation by limiting flexibility to a finite number of options.

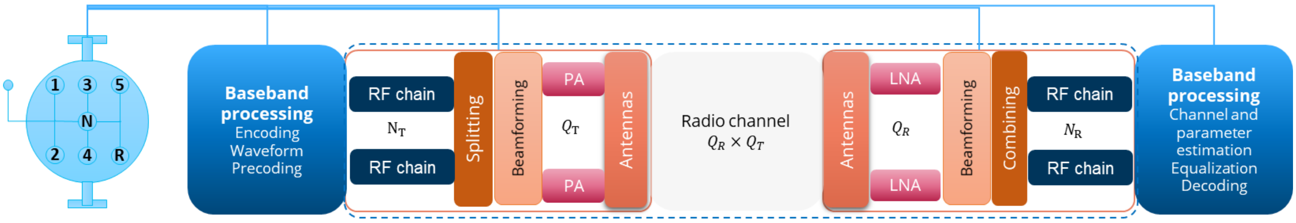

Figure 3-1 Gearbox PHY concept, where each gear represents a specific RF architecture and transmission schemes.

Description: The work related to the gearbox can be divided into two phases. The first focuses on designing the individual gears, and the second aims at optimized operation, as discussed in Section 3.3.1. In the design phase, the gear RF architecture and the corresponding transmission schemes need to be chosen by evaluating different options. Accordingly, the enablers of the gearbox PHY design are flexible hardware architecture and flexible transmission schemes, where each gear is associated with a certain configuration, as illustrated in Figure 3-1.

3.1.1.1 Flexible hardware architecture

The radio hardware architecture consists of the DSP hardware, and analogue hardware, as depicted in Figure 3-2. The DSP hardware handles signal processing tasks in two sub-systems. The first subsystem operates at lower sampling rate and is used for implementing encoding/decoding, modulation/demodulation, precoding, and channel estimation. The second subsystem, referred as digital frontend (DFE), interfaces with the analogue baseband. It performs up-sampling/down-sampling and digital filtering for interpolation/decimation.

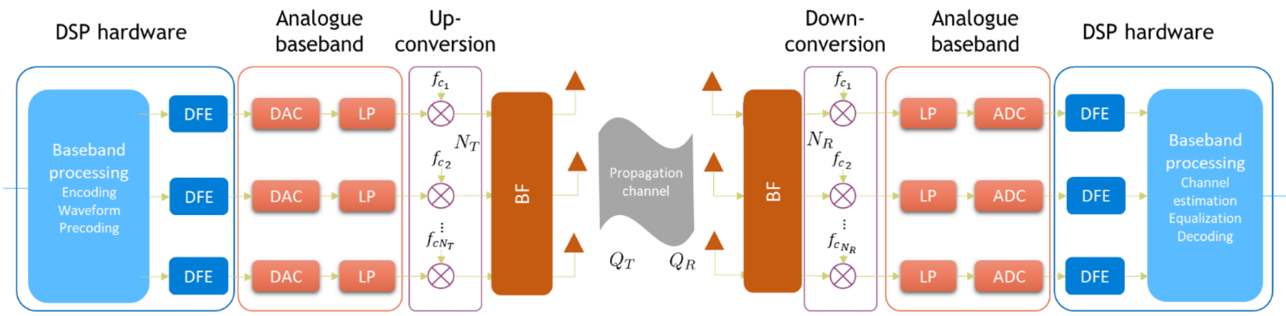

Figure 3-2 Block diagram of flexible hardware architecture.

These DSP hardware components can be general-purposes central processing unit (CPU), DSP, application-specific integrated circuit (ASIC), and application-specific instruction set processor (ASIP). They are usually integrated in modern devices in a system on chip (SoC). The DSP flexibility allows to optimize the processing flow to meet latency and throughput requirements at minimized energy consumption.

The analogue hardware consists of the analogue baseband, frequency conversion modules, and antenna and beamforming modules. The baseband includes DACs/ADCs and LP filtering. The flexibility of this module can be achieved through multiple conversion options regarding sampling rate and resolution, in addition to the number of baseband signal chains. The signal chains are connected to the frequency conversion modules, where flexible tuning of the carrier frequency per chain enables various transmission schemes. In particular, when all the frequencies are tuned to the same carrier, MIMO spatial schemes can be realized, whereas tuning to different carrier allows the implementation of analogue multicarrier or for the realization of multiband. The antenna and beamforming module design depends on the carrier frequency. It can offer multiple antenna options for different frequency bands, as well as varying number of antennas. Note that the frequency conversion can be constrained to a certain intermediate frequency (IF) range, and addition conversion can be integrated in the antenna and beamforming module.

In the context of gearbox, the design of gear involves specifying the required parameters of radio hardware architecture. These include the number of signal chains, bandwidth and resolution per a signal chain, carrier frequencies, and the number of antennas. All unneeded components in the current gear should be turned off for energy saving. Moreover, a suitable DSP configuration needs to be selected in accordance with the signal processing requirements.

3.1.1.2 Flexible transmission schemes

The transmission schemes include transmitter functions such as encoding, waveform, and MIMO precoding, as well as receiver functions like channel estimation, equalization, and decoding. Flexible schemes are necessary to adapt to changing conditions and requirements to maximize performance. Moreover, while different approaches may achieve the same performance, it is relevant to select the approach that improves sustainability. For instance, high reliability could be achieved by means of MIMO space-time coding, or by single-input and single-output (SISO) transmission with a low channel coding code rate. Another example concerns achieving the same data rate either by using a high spectral efficiency waveform with a narrow bandwidth, or employing low spectral efficiency and wide bandwidth. The design of transmission scheme also considers the given radio architecture accounting for different HW constraints. For instance, different waveforms may be needed to mitigate HW impairments at high frequencies, such as PN and PA non-linearity. The waveform type should be compatible with a specific DAC/ADC resolution. Receiver algorithms can also be simplified for a trade-off between complexity and performance.

For the gearbox design, the transmission schemes per gear will be determined based on the gear hardware architecture. In addition, sufficient adaptability within the gear will be provided, which is equivalent to adaptive modulation and coding schemes.

Use cases: The gearbox PHY can be employed in use cases that have a variety of requirements and channel conditions over time and space. For instance, in the "fully merged cyber-physical world" use case, switching to the high spectral efficiency gear takes place before initiating applications that requires extreme data rate, such as holographic communication. This can be triggered by the application layer requesting extreme data rate service. The speed of switching the gear depends on the HW response and loading the corresponding PHY functions. In the ideal scenarios, a low spectral efficiency gear is used to save energy.

KPIs/KVIs: The gearbox PHY will be designed to provide different spectral efficiency level, considering traffic requirements and channel conditions. The available radio resources will be efficiently used in the design of different gears in order to reduce the energy consumption during operation or adapt the capability (e.g., multi-band vs MIMO). A trade-off between flexibility and required hardware resources needs also to be assessed.

Benchmark: The proposed gearbox PHY will be compared with fixed-radio design, such as 5G new radio (NR), where a single hardware architecture and one type of waveforms is used. 5G NR adaptive modulation and coding scheme will be compared with the case of gear switching to assess the energy efficiency for the same KPI performance.

Assumptions: The gearbox PHY serves as a platform for integrating hardware and signal processing schemes, that are selected from available technologies. It focuses on the user plane, assuming the control plane is implemented independently for exchanging the configuration. Moreover, gear switching is a long-term adaptation that is performed less frequently. The switching can be triggered by application requirements, or by the network upon significant changes of the channel and traffic conditions. In contrast, the flexibility within the gear is used dynamically for a short-term adaptation.

3.1.2 Proactive resource management solutions

Interference mitigation and efficient resource utilization is a major challenge in future 6G systems, especially in the context of providing mission critical connectivity solutions. Conventional average based and reactive schemes like hybrid automatic repeat request (HARQ) retransmissions are not suitable for ultra-reliable low-latency communications (URLLC) as they do not accurately capture the tail information of the distribution. Novel solutions incorporating intelligent and predictive approaches are therefore needed to enable URLLC in a scalable and resource efficient manner in future 6G networks.

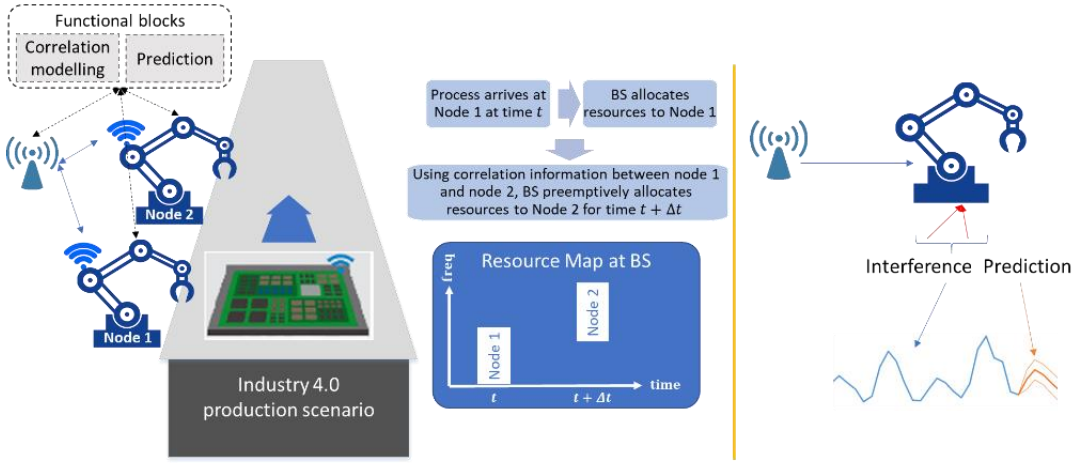

Figure 3-3: Illustration of intelligent proactive resource management in the context of an industrial network.

Description: This work will address intelligent and proactive resource orchestration and interference management solutions based on accurate interference and traffic prediction. The prediction will be made by first accurately modelling the spatial and temporal correlation of the interference/traffic, and then applying a Bayesian inference framework for the prediction. Such an approach captures information about the entire distribution instead of condensing the available information into a single mean value and builds upon existing domain knowledge can improve the prediction accuracy [MLA+21].

Once accurate predictions are made, various novel approaches towards resource orchestration and interference management that utilizes these predictions will be explored. These include the utilization of RIS to favourably shape the transmission pattern and null the interference [JY22]; use of interference alignment techniques to coordinate the interference generated at unintended devices [GPK09]; interference coordination schemes to proactively protect mission-critical users requiring high performance guarantees [SDB+18]. An illustrative example is shown in Figure 3-3.

Use cases: This work targets ensuring critical connectivity and hence the applicable use cases are: i) Digital Twins for manufacturing, ii) Fully merged cyber-physical worlds, and iii) Interacting and cooperative mobile robots.

KPIs/KVIs: The relevant KPIs and KVIs to evaluate this enabler are latency and reliability/outage performance and resource efficiency.

Benchmarks: URLLC enablers in 5G NR will be considered as benchmark.

Assumptions: The work is primarily focus on downlink transmission and assume that control channels are in place to exchange the necessary information for prediction and coordination.

3.2 Inclusive radio interface via TN/NTN enhancements

Achieving ubiquitous connectivity is among the goals of 6G, necessitating a seamless integration of TN with NTN. This section presents potential enhancements of TN/NTN integration aligned with 3GPP standards. In addition, it explores the role high altitude platform stations high altitude platform station (HAPS) to bridge both urban and remote terrains.

Inclusive radio interface integrating TN with NTN, including HAPS has the potential of providing ubiquitous connectivity for multiple 6G use cases. This includes providing connectivity to poorly connected remote and rural areas, as well as providing connection diversity for critical applications in urban areas such as smart cities and smart logistics applications, and in the case of disasters or loss of infrastructure [KKA+21]. A HAPS is a network node that operates in the stratosphere at an of altitude around 20 km and HAPS mounted base station can serve as an intermediate layer between satellites and the terrestrial network. The main challenge is the convergence of multiple different technologies such that they can seamlessly coexist and provide un-interrupted service with acceptable costs and complexity. Due to their different altitudes, satellites and HAPS can provide complementary solutions.

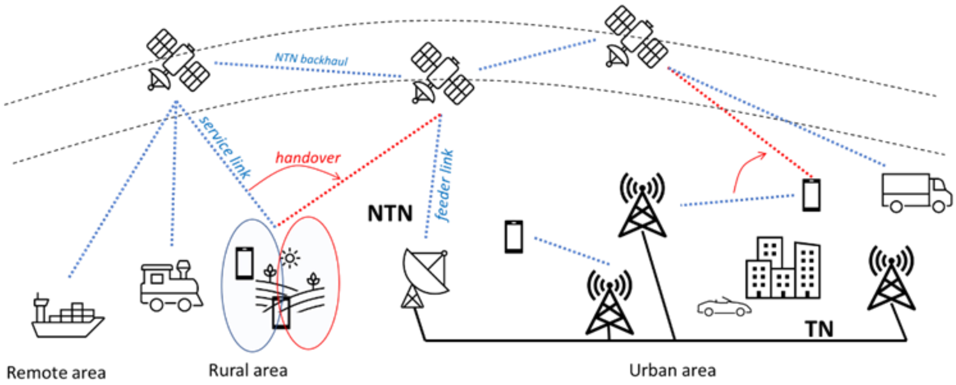

Figure 3-4 TN/NTN enhancements for inclusive connectivity.

During 5G-era, NTN research has gradually shifted to industrial standardization. From 2017, 3GPP started studying deployment scenarios, channel models, and use cases for NTN in Release 15, solutions for 5G NR to support NTN in Release 16, and worked on system aspects and RAN-related specifications in Release 17. Currently, in Release 18, additional work on NTN is ongoing to define various enhancements towards 5G-Advanced leading into early 6G systems, including aspects such as coverage, deployment in above 10 GHz bands, network verified UE location, mobility and service continuity, and NTN-IoT enhancements.

Description: The plan of this work is to develop air interface enhancement solutions in-line with 3GPP standardization work throughout the project lifetime. Solutions will initially consider enhancements on mobility and service continuity procedures (e.g., handover, cell reselection) to address NTN characteristics, such as large propagation delay and satellite movement. It is planned to analyse other existing proposed solutions and specification proposals, identify their limitations, and introduce new efficient schemes that address those limitations. Furthermore, a feasibility study is planned of integrating TN and HAPS mounted network. This will include studying the link quality, the coverage area and multi-connectivity performance.

Use cases: TN/NTN integration enhancement enabler targets at improving access and reliability in rural and/or remote areas. Thus, it can be beneficial to use cases that require crucial services everywhere or for backup connection, such as the “E-Health for all” use case for providing coverage at home, outdoors, and ambulance scenarios.

KPIs/KVIs: The relevant KPIs and KVIs to evaluate this enabler will mainly depend on the area of improvement of the developed solutions. For example, for the topic of handover (HO) improvement, the most relevant KPI regards the signalling overhead. In addition, coverage improvement can be measured in terms of the coverage area with a given minimum received signal strength.

Benchmarks: The Rel-17 NTN architecture and features will be considered as benchmark.

Assumptions: The assumptions also considered currently in Release 18 NTN standardization work will be followed, including sub-6 GHz bands, GSO and NGSO network scenarios, transparent payload, 3GPP power class 3 UE (23 dBm) with GNSS capability, as well as earth fixed or moving cell NTN configurations.

3.3 Sustainable radio solutions

To contribute to 6G sustainable target, two approaches are highlighted in this section. Firstly, the "gearbox PHY" approach allows radios to switch between different modes for more energy-efficient operations. It adjusts based on various conditions and requirements to choose the most energy-saving 'gear'. Secondly, the emerging field of "semantic communication" uses goal-driven methods rather than traditional data transmission models. By using machine learning, this method tailors encoding to specific tasks, potentially leading to more efficient and meaningful communication in applications like IoT and smart cities.

3.3.1 Optimization framework for gearbox PHY switching

The gearbox PHY concept presented in Section 3.1.1 provides flexible radio options and transmission schemes. For the operation, it is required to determine the gear switching conditions, and select the appropriate schemes within the gears to achieve the required KPIs at lower energy consumption. This requires an optimization framework to assess different conditions to give the switching decision.

Description: As illustrated in Figure 3-5, the optimization framework for enhancing energy consumption takes as inputs the available hardware and radio resources, the communication requirements (data rate, latency, reliability), and channel conditions (wireless channel and interference). The objective is to determine the most energy-efficient gear for long-term switching and configure the current transmission parameters within the selected gear. Gear switching is based on statistical conditions measured by the network for a long period, in in addition to the consideration of service requirements, while short-term optimization is equivalent to adaptive resource allocation. This can be made programmable and manageable through an exposure layer such that intents from the management and orchestration layer be used. For instance, an application may request certain requirements at the initialization phase, the network decides based on the requirement and the conditions to switch the gear. During the application runtime, short term optimization to determine the transmission parameters. By completion of the application, the network will trigger another change of the gear.

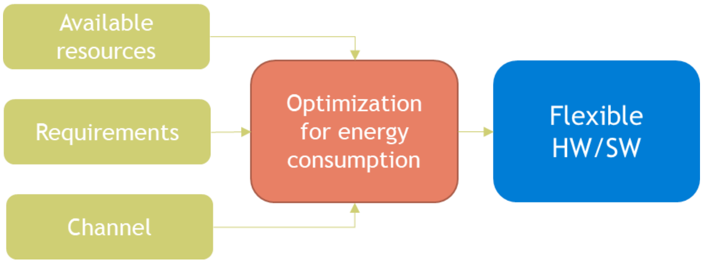

Figure 3-5 Gearbox optimization framework

Use cases: The gearbox PHY use cases are presented in Section 3.1.1.

KPIs/KVIs: As discussed in in Section 3.1.1, the focus is to achieve KPIs at low energy consumption.

Benchmark: The optimization of resources per gear is similar to resource allocation in 5G NR. However, the improvement in energy efficiency will be evaluated considering the use of an optimized HW/SW architecture per gear.

Assumptions: This framework operates on top of a gearbox PHY with specified gears in terms of hardware architecture and transmission schemes. It is also assumed that channel measurements and other inputs are available.

3.3.2 E2E optimization framework for energy efficiency

Description: The road to future wireless networks encourages an evolution beyond conventional bit-oriented Shannon transmission bounds. At the heart of this evolution lies goal-oriented semantic communication. Recently, semantic communication has gained much attention [GQA+22]. However, the conceptual level of semantic communication still needs proper research and a path toward standardization. Therefore, efforts are required for many semantic communication scenarios, for instance, image/video transmission, telemetry, and factory automation. The objective of this study is to identify key scenarios and applications for semantic communication and propose a machine-learning-based framework for semantic encoding for the different applications [LWZ+21]. Semantic encoding is a joint source and channel coding solution beneficial in dense networks with heterogeneous services. The target is to exploit feedback from the executed tasks to train a task-oriented deep-meta-learning network to perform semantic encoding for each channel-application pair, as shown in Figure 3-6. That is, the encoding is differentiated and optimized for each application, with limited training overhead. This is possible with the use of Meta-Learning [FAL17], which is a concept related to "learning to learn" and aims at solving many tasks that are different but related to each other through acquiring a shared parameter, "the prior", among the learning model. Therefore, applying deep meta-learning here would expedite training the semantic encoders for new tasks rather than learning them from scratch. In this sense, the amount of data to be delivered would be smaller and the E2E optimization of the whole network would lead to significant boost in energy efficiency.

Research in semantic communication is still in its infancy and lacks standardization. An important endeavour is to promote one of the first few standardization efforts for general and/or vertical-specific semantic encoding. This could be carried out in the future with vendor companies once the output of this research is solid and well-defined. The used tools in this work may include machine learning, probability theory, optimization, MATLAB, and Python.

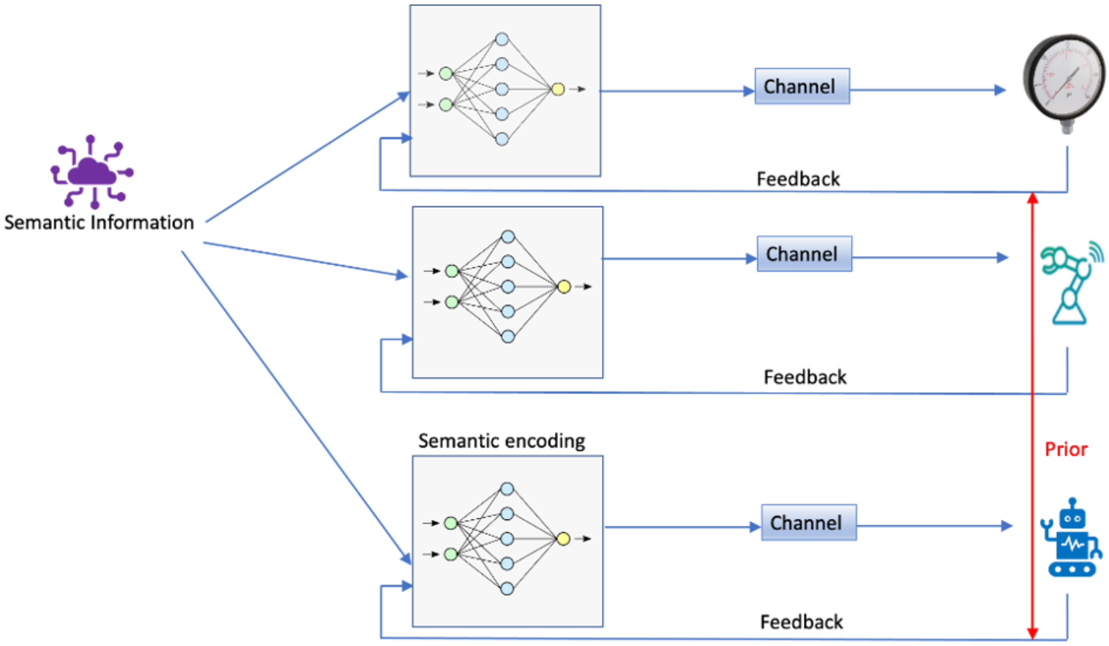

Figure 3-6 Task-oriented semantic encoding

Benchmarks: Conventional Shannon models – Conventional channel capacity – Information theory tools

Use cases: This research scheme could be widely applied in industrial and autonomous vehicles applications within the next few years. Semantic communication has been the prime impetus for the evolution of post-Shannon paradigm, owing to perpetual growth in user requirements for various applications such as IoT for smart cities, digital twin for industrial applications, virtual & augmented reality, and ultra-high-resolution sensors. This research is focused on ML-based mutual semantic representation. This novel work will prove an important milestone in industrial deployment of semantic communication as it aims to deliver real-world observations of physical entities and their judicious mapping to meaningful concepts in speaker domain for continual evolution of joint semantic catalogue for the overall network and successful entity inference from these concepts (concept-to-entity (C2E)) received in listener domain of each participating node. The focus of semantic communication is retrieval of semantic context of the desired message in contrast to the conventional notion of bit recovery regardless of human reasoning. The long-standing Shannon-Weaver model of communication is bound by probability of symbol error, information rate and channel capacity, which are being challenged by emergent semantics concepts dependent upon modern ML techniques.

Pragmatic application of the proposed research will make emergent semantic communication technologies capable of massive connectivity in Beyond 5G networks as it conceptualizes a comprehensive solution for reliable semantic context transmission. Mutual Semantic Representation (SR) for multi-node network will enable post-Shannon precepts to be realized from theoretical abstraction to heuristic and cognitive reality. 6G cellular networks, vehicle-to-anything communication (V2X), and industrial scenarios wireless sensor can be the main beneficiaries of this propounded framework in terms of substantial capacity enhancement and reliable context delivery.

KPIs: Energy efficiency – Energy consumption – Accuracy of transmission – Task success rate.

Assumptions: E2E communication / industrial scenario where a certain task is being performed.

3.4 Trustworthy radio solutions

This section highlights solutions that prioritize security and resilience in 6G Radio. The "PHY Security" approach leverages Secret Key Generation (SKG), utilizing the physical layer for more lightweight security. It exploits channel variations to create shared secret keys, ensuring safer communications especially against eavesdroppers. It is particularly suitable for real-life device pairing scenarios, offering a potential alternative to conventional encryption methods. On the other hand, jamming resilience schemes are crucial for critical communication scenarios, ensuring that services remain uninterrupted even under intended interference, like jamming. Techniques at the physical layer, like spread spectrum, can be employed to combat these threats. This approach aims to ensure that crucial communications remain robust against both conventional disruptions and malicious attacks.

3.4.1 PHY security

Secret key generation (SKG) using physical layer security is a lightweight solution to implement the security in the physical layer especially in use cases requiring low computation power, memory and energy consumption. The channel reciprocity between the legitimate users is utilized to extract a shared key. The independent stochastic component of the channel fading provides the source of randomness and due to spatial decorrelation, the channel observed at the passive eavesdropper is uncorrelated to that of legitimate users. The SKG protocol consists of four steps: randomness extraction, quantization, information reconciliation and privacy amplification. During the first phase, two legitimate users exchange pilot signals during the coherence time of the channel and obtain channel observations given. Due to the reciprocity of the wireless medium, they have correlated measurements, dependent random variables. An eavesdropper can observe the exchange and obtain an observation (which may be or may not be correlated to that of legitimate users). All observations are quantized to binary vectors. Due to factors such as noise, RF-chain impairments, imperfect reciprocity, etc., the legitimate users may not have identical binary vectors. To correct errors information reconciliation is performed using distributed source coding techniques, where one of the parties shares side information over a public channel. During privacy amplification stage, the information leaked during the channel probing phase and information reconciliation phases are estimated and compressed to obtain a secret key via one-way collision resistant functions (e.g., SHA-256). As a result, SKG requires only the use of standard codes and a hash function and has very low complexity. SKG is the counterpart of quantum key distribution (QKD) in non-quantum channels.

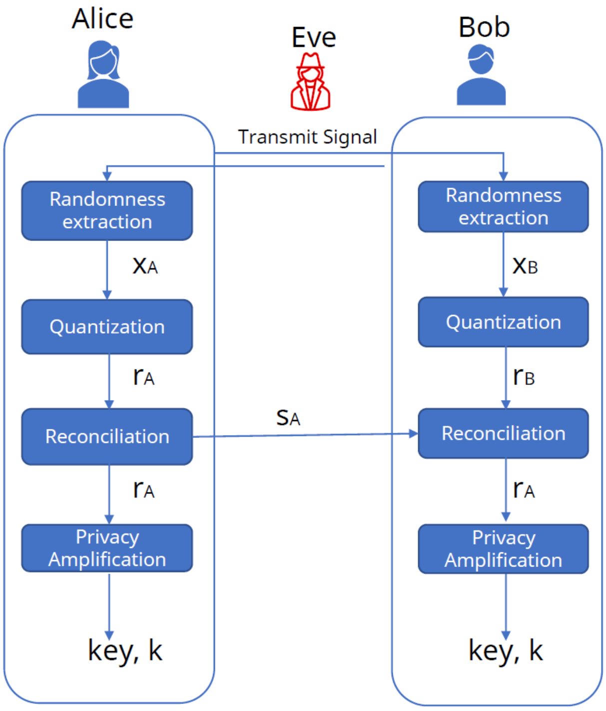

Figure 3-7: Secret Key Generation protocol illustrating passive eavesdropper.

Description: This work aims to investigate the feasibility of SKG in real life device pairing scenarios for device-to-device (D2D) communications in the presence of passive eavesdropping attackers. This can be used in any uplink and downlink communication scenarios when both the devices exchange known pilots with each other within the channel coherence time. The aim is to evaluate the SKG rates at different measurement environments and design space, i.e., the design parameters used at different stages of the SKG protocol. In this model, passive eavesdropping attack is considered, and the information leaked to the eavesdropper placed at different locations w.r.t the legitimate users will be evaluated. This work comprehensively studies the realizability of the SKG in different fading channels on the measurement data collected and identifies the optimum design parameter combination to achieve maximum SKG rates.

Use Cases: The PHY Security based SKG aims to provide lightweight solutions requiring low computation power and complexity. SKG can be used as a complementary security measure in certain use cases along with traditional cryptographical algorithms or as a standalone implementation where security is implemented in the physical layer. *Fully merged cyber physical world* is a use case for this work.

KPIs/KVIs: The potential information leakage to the eavesdropper dependent on the design space parameters, channel measurement environment and the achievable key rates

Benchmarks: N/A

Assumptions: The pilot signal exchange to obtain the received signal measurements between the devices should follow TDD scheme. Passive eavesdropping attack is considered as the threat model.

3.4.2 Jamming resilience schemes

Communications for critical use cases have to be robust in order to provide seamless service avoiding potential damages. This requires not only being reliable against the typical fluctuations, such as the random fading of a wireless channel, but also being prepared for adverse events. In the context of wireless communications, a crucial adverse event is given by the threat of jamming: a potential aggressor could potentially disrupt communications with relatively simple means by jamming parts of the spectrum, with dramatic consequences on the application side. Such a threat has to be detected and an appropriate reaction may be initiated on different (or several) layers. E.g., the application could be informed in order to switch sufficiently early into a safe state, or the network may try to use alternative routes, radio resources and/or access points. At the lowest layer, a flexible PHY could offer different transmission modes that might be more suitable to detect jammers or that are more robust against jammers, e.g., by using techniques like spread spectrum that are more difficult to jam. Here, it needs to be studied, how these modes should be designed and whether it make sense to use them preventively for critical communications or for less critical services only as a reaction when an attack is detected. In addition, the system has to be resilient also against other kinds of failures (apart from jamming) in order to be suitable for mission-critical applications.

Description: After defining adequate threat scenarios, appropriate schemes will be developed and evaluated against the scenarios in order to show their effectiveness and limitations. At the PHY level, this includes more robust schemes or transmission modes that are more difficult to jam (see above).

Use Cases: This work is mostly related to all critical use cases, i.e., all use cases with severe consequences, when communication is interrupted.

KPIs/KVIs: Jamming classification accuracy, bit error rate in jammed scenarios, availability metrics.

Benchmarks: A convolutional neural network-based radar jamming recognition framework to enhance the resiliency through anti-jamming capabilities is studied in [LG22]

Assumptions: It is assumed that the E2E system detects the threat and may also react accordingly.

4 Radio link modelling

This chapter addresses the contributions related to radio link modelling for 6G systems. 6G is envisioned to exploit new frequency bands, namely, the 7–15 GHz range and the (sub-)THz range (above 100 GHz). The latter is particularly promising to unlock data rates up to Tbps speeds and enable specific 6G use cases. While the 7–15 GHz range exhibits propagation properties that are close to those of 5G frequency bands (as it is located between FR1 and FR2), the sub-THz range is prone to molecular level attenuation, impacting propagation and channel modelling. Thus, implementing high-frequency systems requires a thorough understanding of the signal's behaviour in every possible new scenario. Furthermore, new link-level modelling and simulations should be developed to fully map the effects of these higher frequencies on different communication systems. Hence, the contributions are divided into three main topics: channel modelling, coverage analysis, and link modelling. The first section discusses channel modelling for sub-THz frequency bands by providing stochastic and deterministic models to characterize fading, blockage and other propagation phenomena. The following section introduces a coverage analysis of THz communication systems, considering all propagation losses and other frequency-related challenges. The aim is to estimate the covered area and its impact compared to other frequencies, i.e., 100-300 GHz. Finally, the link modelling section presents two simulation tools for the 6G PHY layer and RIS systems. The former plans to understand the performance of the PHY layer processing chain operating in mmWave and sub-THz frequencies. The latter proposes a simulator to investigate the effects of RIS in relayed communication with specific gain and radiation patterns.

4.1 Channel modelling

Communications at (sub-)THz frequencies are subject to strong pathloss and penetration loss and rely predominantly on LoS conditions. It is thus crucial to build a suitable channel model to assess the potential and main limitations range in terms of signal propagation in the (sub-)THz. This section describes the work on channel modelling and coverage analysis at (sub-)THz frequencies.

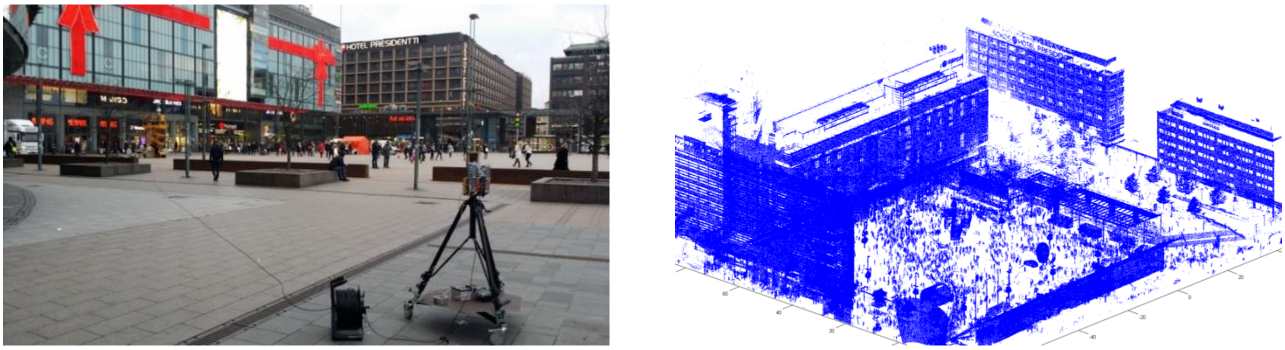

Figure 4-1 Channel measurement campaign in the centre of Helsinki (left); geometry of Helsinki city centre for ray-tracing simulations (right).

4.1.1 Channel models at Sub-THz frequencies

The propagation channel is dependent on many factors such as object blockage, mobility of objects and antenna, electromagnetic properties of the objects, and all of which vary depending on the site and scenario being considered. This work will provide models for fading, blockages, and other propagation mechanisms from 100–300 GHz, and possible provide comparison analyses with cmWave frequencies.

Description: The initial task is to generate multiple-frequency channel datasets. This is followed by analyses of results to understand and represent the behaviour of propagation factors such as multipath, doppler spread, human blockage attenuation, and penetration/reflection losses for different materials. A scenario-specific and site-specific channel models are considered to determine the feasibility of establishing link and determine the coverage in various scenarios and sites. Here the aim is to provide guidelines of different modelling framework, e.g., stochastic and deterministic models.

Use cases: The channel model can be used to evaluate wireless transmission schemes with realistic channel impairments considered and for coverage study at sub-THz frequencies.

KPIs/KVIs: The main KPIs to be considered are SNR and coverage.

Benchmarks: The large- and small-scale parameters of the generated channels can be compared with existing channel modelling frameworks, e.g., 3GPP [38.901] and ITU-R [M.2412-0].

Assumptions: The channel models are based on measurement data obtained from a limited number of mostly static environments. One aspect of the dynamic channel is the human blockage effect which will be considered as an add-on feature of the channel model to be developed. Also, only representative incident angles are considered in the study of material losses.

4.1.2 Coverage analysis at THz frequencies

THz frequencies (300 GHz–3 THz) are located between mmWave (30–300 GHz) and far infrared (3–20 THz) and provide increased bandwidths (in the order of tens up to hundreds of GHz) compared to the ones achievable with mmWave, leading to meet the demands for increased data rates up to Tbps. The countereffect is represented by a conspicuous reduction of radio coverage compared to the one achievable with mmWave, due to the experienced high propagation loss. THz frequencies are therefore suitable for providing focused coverage spots in the range of roughly 1 m – 100 m, depending on the considered frequencies and available bandwidths.

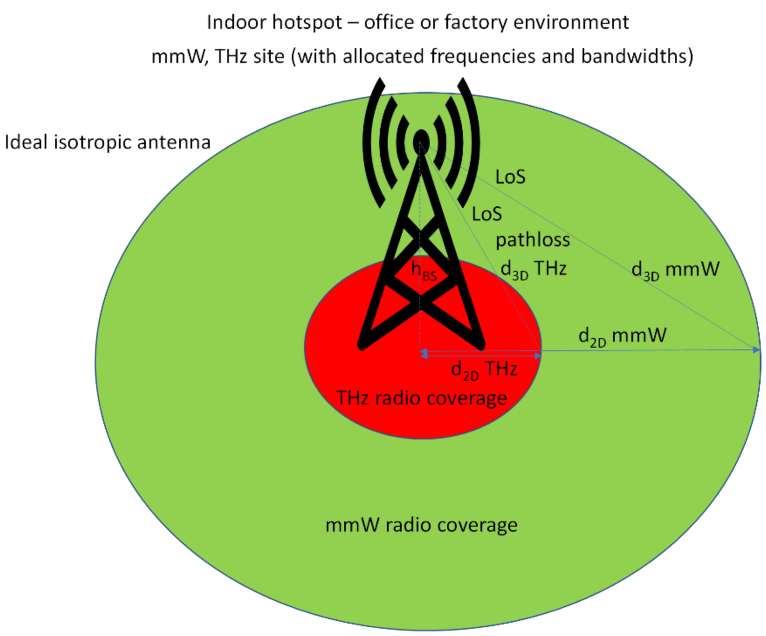

Figure 4-2 THz frequencies impacts on the achievable radio coverage compared to the one achievable with mmWave.

Description: The propagation loss challenges posed by THz frequencies are analysed in case of LoS in terms of e.g., spreading loss and molecular absorption loss and in case of non-line-of-sight (NLoS) also in terms of e.g., reflection loss and scattering [HWC+22, ECM+22, JSJ+19]. The target is to provide an estimation, based on theoretical analysis, in terms of radio coverage impacts compared to the one achievable at 100-300 GHz.

Use cases: By meeting the demands for increased data rates up to Tbps, the proposed enabler can be beneficial in the most data-hungry services envisioned in "E-health for all" and "Fully merged cyber-physical worlds" use cases.

KPIs/KVIs: The considered KPI is the coverage reduction compared to 100–300 GHz coverage, quantified by pathloss evaluation, and considering the achievable ranges in terms of distances and the considered frequencies with the available bandwidths. The considered KVI is inclusiveness, due to increased bandwidths and data rates up to Tbps that allow to enable services like immersive communications and “Fully merged cyber-physical worlds”.

Benchmark: Coverage achievements at 100-300 GHz representing the performance upper-bound.

Assumptions: It is considered a LoS scenario without multipath effects, with ideal isotropic antennas at both transmitting and receiving side. It is assumed the availability of coverage analysis at 100-300 GHz, with operator-based considerations on coverage coming from the enabler dealing with scenario-specific and site-specific channel modelling, mainly at 100–300 GHz.

4.2 Link-level signal modelling

The channel modelling discussed in the previous section is integrated with antenna models, RF properties, and digital signal processing at the transmitter and the receiver to build a full link-level signal model. By including the effect of factors such as waveforms and modulations, transceiver implementation constraints, hardware impairments, and beamforming, the work in this section allows to provide a comprehensive picture of the potential and main limitations of communications in the (sub-)THz band.

4.2.1 Link modelling of 6G physical layer

A link-level simulation tool of the 6G PHY will be developed, including models of multi-cluster propagation channels in the sub-THz bands. The simulator will provide performance evaluation of enhanced physical-layer schemes, e.g., D-MIMO, beamforming, and evolved coding. The aim is to understand the impact of enhanced physical-layer schemes, to improve the system performance and to optimize the parameters, especially in mmWave (FR2 frequency bands) and sub-THz context.

In this deliverable some reference scenarios are defined, and first simulation results are provided, e.g., BER versus SNR curves. These reference results will be compared with the proposed enhancements in the next deliverables.

Description: The simulation chain presented in Figure 4-3 will be implemented, based on the 3GPP specifications [38.104], [38.211], [38.212]. The blocks are developed in Python, using the Sionna open-source libraries as a starting point [Hoy22], offering substantial flexibility in the development, choice of the use cases, etc. It allows the integration of new algorithms/configurations so that the chains can easily evolve.

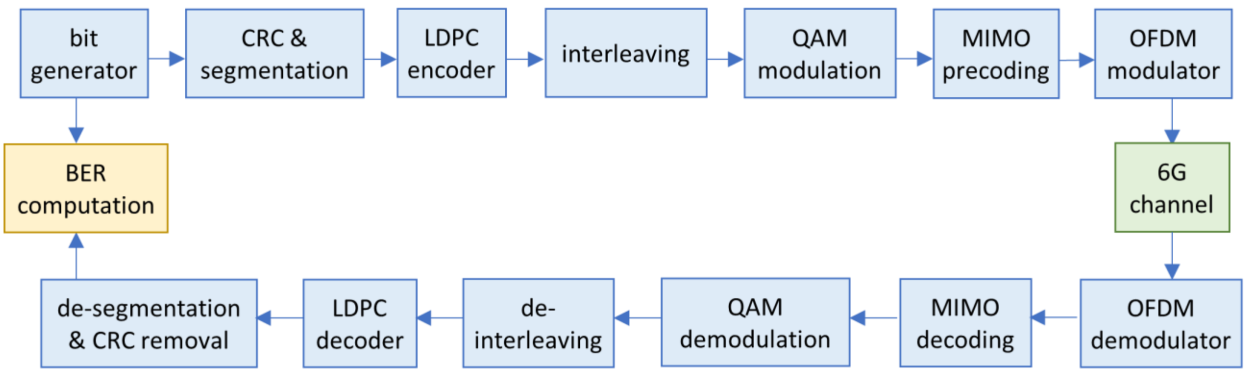

Figure 4-3 Diagram of the 6G PHY layer simulator.

The bit flow is randomly generated by a bit generator, and feeds the chain of baseband signal processing blocks: segmentation, cyclic redundancy check (CRC), interleaving, etc. The forward error coding scheme is the LDPC. OFDM modulation is achieved, and the signal samples are convolved with a randomly generated channel impulse response. The reception part of the chain includes the demodulators and decoders, leading to an estimation of the transmitted bits. A dedicated block compares the initially generated bits with the estimated bits and computes the BER and block error rates (BLER).

The first version of the simulator includes an ideal MIMO precoder/decoder (e.g., based on the single values decomposition of the channel matrix). The obtained BER vs. SNR results will be used as reference, and further compared with other MIMO schemes, such as D-MIMO and hybrid beamforming.

The fast-fading channel model is initially based on the 3GPP specification [38.901], which is valid for carrier frequencies ranging from 0.5 to 100 GHz. This model should evolve towards higher frequencies.

Use cases: The aim of the simulator is to evaluate the KPI/KVI of the 6G PHY layer in a large variety of contexts (spectrum, environment, etc.), therefore it can be used to determine whether the conditions of the use cases defined in WP1 are met.

KPIs/KVIs: The simulations will provide the following metrics: BER, BLER, SNR, spectral efficiency, throughputs.

Benchmarks: The reference classical 5G MIMO configuration will be compared with enhanced D-MIMO schemes. For a given target BER, a gain over the SNR is expected, which leads to a better link budget, hence, an improved cell coverage.

Assumptions: The proposed link-level simulator is defined at the baseband level, but RF aspects are not modelled. The signalling is not modelled so that only data bits are implemented. The transceiver-receiver synchronization is assumed to be perfect, and the channel is assumed to be perfectly known, channel estimators are not evaluated in this study.

4.2.2 Hardware modelling of RIS

A Hardware model of a RIS will be needed for creating a link-level simulation for radio systems including a RIS. Signals that are relayed by a RIS are forwarded with a specific relay gain and radiation pattern.

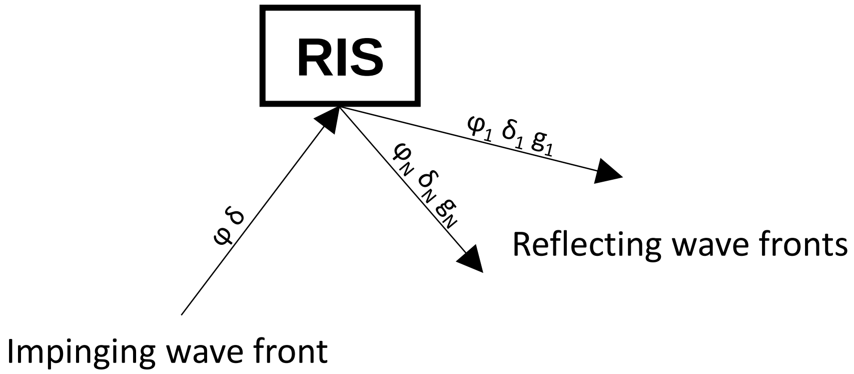

Figure 4-4: RIS simulation model

Description: For the simulation model regarding the RIS, MATLAB is used to calculate and simulate the radiation patterns of the RIS. The results will consist of real-valued isotropic relay gain values of the RIS for horizontal and vertical polarization as a function of elevation and azimuth angle. Input variables to the simulator of the RIS are the desired incoming and outgoing signal directions (one elevation and one azimuth value each), the polarization of the incoming signal (vertical or horizontal) and the FR2 operation centre frequency.

Use cases: RIS hardware modelling is beneficial in use cases where radio propagation is or can be hindered by the presence of obstacles such as in urban or industrial environments as “Interacting and cooperative mobile robots”, “Small coverage, low-power micro-network in networks for production and manufacturing” and “Immersive smart city”. Short-range mobile communication in the FR2 frequency band is considered.

KPIs/KVIs: Relevant KPI is radio coverage achievable with RIS. Relevant KVI is Reliability given the ability of RIS to introduce spatial diversity in the radio propagation environment.

Benchmarks: The simulation results will be compared to measurement results that have been obtained with a RIS prototype operating in the FR2 frequency band.

Assumptions: In the simulation, the effect of the RIS is based on learnings and measurements of one known RIS realization. The results therefore will match the effects of one realization closely but might deviate depending on the used RIS technology.

5 Waveforms and modulations

This chapter covers waveform design and modulation schemes for THz-based communications. Waveforms and modulation schemes are the main pillars of spectral and energy efficiency. With multiple carriers, the transceiver can provide higher spectral efficiency and data rates at the cost of increased power consumption. However, this scenario is prohibitive for mobile communications, since the user equipment has well-known energy constraints. Also, as discussed in other chapters, THz-based signals are highly susceptible to attenuation than other frequency bands, requiring more sophisticated energy-saver transceivers.

The contributions of this chapter tackle these questions by analysing traditional waveforms and providing new solutions for THz-based systems. The first section analyses the feasibility of mainstream waveforms for 6G systems operating at sub-THz frequency bands. The objective is to evaluate the performance of OFDM and single-carrier (SC) -based waveforms to enable higher data rates and investigate their energy efficiency, PN tolerance, and scalability over high bandwidths. The next section proposes the zero-crossing modulation (ZXM) scheme to reduce the power consumption of ADCs with 1-bit quantization. Another contribution discusses briefly learned MIMO waveforms and their ability to obtain the waveform without pilot detection at the receiver side. Finally, the last contribution introduces polar constellations for any frequency bands and other scenarios, such as high mobility. The aim is to create a constellation robust to PN and Doppler shift.

5.1 Feasibility of the mainstream 6G waveforms at sub-THz frequencies

The performance of potential 6G waveforms, such as OFDM and SC-based waveforms, have been compared for lower carrier frequencies in [HEX21-D22, Section 4]. Sub-THz will be the next step to expand from the mmWave band towards higher frequencies, enabling Gbps and even Tbps data rates. With sub-THz frequencies, transceiver impairments, such as phase PN and PA distortions, will increase even further, resulting in coverage issues and flawed energy efficiency. Unfortunately, in this scenario, PN compensation is quite challenging and large output power back-off is required for PAs. Additionally, very high bandwidths are needed to attain Tbps rates with sub-THz frequencies. Due to larger bandwidths and massive antenna arrays envisioned to compensate for the increased propagation attenuation of THz channels, PA linearization becomes a challenging problem. Therefore, it is needed to carefully investigate a proper waveform to accommodate the needs of sub-THz bands.

Description: This work aims to study the feasibility of the mainstream 6G waveforms – primarily designed for lower frequency bands – for sub-THz frequencies. The analysis will focus on the suitability of the waveforms for sub-THz frequencies, considering demands such as increased energy efficiency, PN tolerance, and scalability over high bandwidths and different frequency band combinations. The candidate waveforms include OFDM and SC-based waveforms, i.e., discrete Fourier transform spread orthogonal frequency-division multiplexing (DFT-s-OFDM) and known-tail discrete Fourier transform spread orthogonal frequency division multiplexing (KT-DFT-s-OFDM).

Use cases: Sub-THz spectrum bands can cope with very high area capacity in traffic hot spots with short-range communication, such as device-to-device communication. Equally important are long-range fixed and mobile wireless links for access and backhaul. In this regard, the waveform study for sub-THz is the core of the 6G communication system and thus relevant for all the top 6 use cases introduced in Section 2.3.2, and especially, for energy-optimized services, digital twins for manufacturing, fully merged cyber-physical worlds, and interacting and cooperative mobile robots.

KPIs/KVIs: The key KPIs are the waveform's energy and spectral efficiency, PN tolerance, and scalability over different frequency bands. Network densification is another aspect affecting sub-THz deployment, and this will be considered as a KPI while studying the candidate waveforms for the sub-THz.

Benchmarks: The performance of the waveforms on lower frequencies, cyclic prefix (CP)-OFDM as the baseline on the sub-THz bands.

Assumptions: The studied waveforms will be utilized also in the lower 6G bands.

5.2 Zero-crossing modulation

6G wireless communication systems are expected to leverage the abundant spectrum available in the mmWave and sub-THz bands (above 100 GHz) to support the escalating demand for high-speed data transmission. However, utilizing conventional system designs at these frequencies may lead to a significant energy-efficiency bottleneck caused by the power consumption of ADCs. To tackle this challenge, a resolution shift at the ADC from the amplitude domain to the time domain may provide a more energy-efficient solution, which can be implemented by 1-bit quantization and temporal oversampling the Nyquist rate at the receiver [ZGR18]. As 1-bit quantization is a highly non-linear operation, it makes the redesign of modulation and receiver algorithms necessary. To this end, ZXM modulation scheme [FDB+19] will be further investigated.

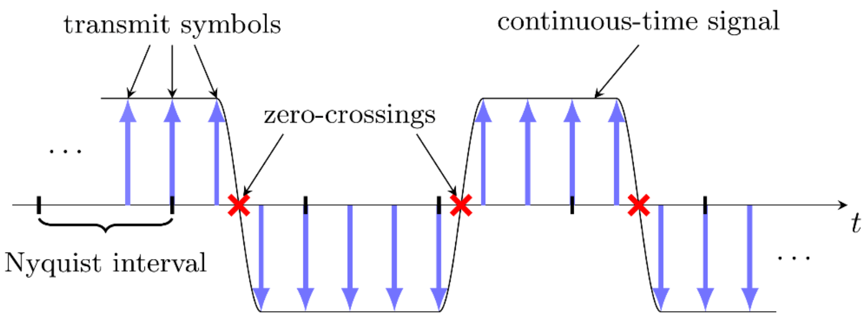

Figure 5-1 Sketch of a ZXM transmit signal, taken from [STP+23].

Description: The power consumption of ADCs is known to depend exponentially on the amplitude resolution, measured in bits [Wal99]. Therefore, to address the issue of high ADC power consumption, one possible solution is to reduce the amplitude resolution. In the extreme case, the use of 1-bit ADCs promises receiver designs with relaxed linearity constraints on the analogue frontend and receivers without the need for automatic gain control. However, 1-bit ADCs are only capable of resolving the zero crossings of the received signal. To transmit information in such a system, the temporal distance between zero crossings of the transmit signal can be used as a natural way of conveying information. Modulation schemes that encode the information in the distance between zero crossings are called ZXM and one possibility to create a ZXM transmit signal is to combine faster-than-Nyquist signalling (FTN signalling) and runlength-limited (RLL) sequences [LDF18]. To create RLL sequences, binary (d, k)-sequences can be utilized, where every 1 must be followed by at least d zeros, but no more than k zeros. These RLL sequences can then be generated through a process known as non-return-to-zero inverted (NRZI) encoding, which encodes data bits as transitions between signal levels rather than the absolute signal level itself. The NRZI encoding process can be illustrated through the following example:

$$(d, k) \quad \bar{\boldsymbol{a}}_m = [\dots, -0, -1, -0, -1, -0, -0, -1, \dots]^T \tag{5-1}$$

$$\text{RLL} \quad \bar{\boldsymbol{a}}_m = [\dots, -1, +1, +1, -1, -1, -1, +1, \dots]^T \tag{5-2}$$

While FTN signalling can lead to self-introduced inter-symbol interference (ISI), this can be controlled by selecting an appropriate d constraint for the RLL sequence. Although the use of RLL codes reduces the rate, this reduction is overcompensated by the benefits of FTN signalling. As a result, more than 2 bit/s/Hz can be achieved [NDF21]. A ZXM transmit signal is schematically shown in Figure 5-1.

Use Cases: As ZXM is mainly tailored towards energy-efficient data transmission, it can be seen as an enabler for energy-optimized services in 6G.

KPIs/KVIs: ZXM's key KPIs include spectral efficiency and stability in the presence of non-idealities, such as PA non-linearities and PN. Additionally, the energy spent per bit is the most important KVI for ZXM, reflecting its emphasis on energy-efficiency.

Benchmarks: ZXM aims at enhanced energy efficiency and can be benchmarked against systems with conventional high-resolution ADCs and conventional modulation schemes such as OFDM.

Assumptions: The practicality of implementing the ZXM waveform in 6G depends on the chosen PHY architecture. While ZXM is not intended to be the primary waveform for all use cases, it is suitable for scenarios requiring high data rates in the presence of ample spectrum. Therefore, the feasibility of ZXM is contingent upon the existence of a versatile PHY layer, such as the Gearbox-PHY, as envisioned in recent proposals [FB21] and, e.g., Section 3.1.1.

5.3 Polar constellations

For some 6G use cases deployment, the use of carrier frequencies in the THz band seems to be interesting for high data rate indoor environment. At this carrier frequency the oscillators integrated in such device are not very accurate leading consequently to a greater lack of synchronization and PN. Furthermore, the technical proposal is agnostic to any frequency band and could be also used for frequencies below 6 GHz and interesting for high mobility speed that entails doppler shift. Both phenomena, high frequency and/or high mobility speed, will induce rotation of the constellation (bits to symbols mapping) at the receiver. The goal is to create new types of constellations robust to PN and doppler shift. It is denoted as "polar constellations". In the design, polar constellations are combined to a multicarrier waveform like cyclic prefix orthogonal frequency division multiplexing (CP-OFDM). Those new types of constellations induce to implement an advanced (but simple) demodulator designed to correct the common phase error (CPE) of the received polar constellations symbols.

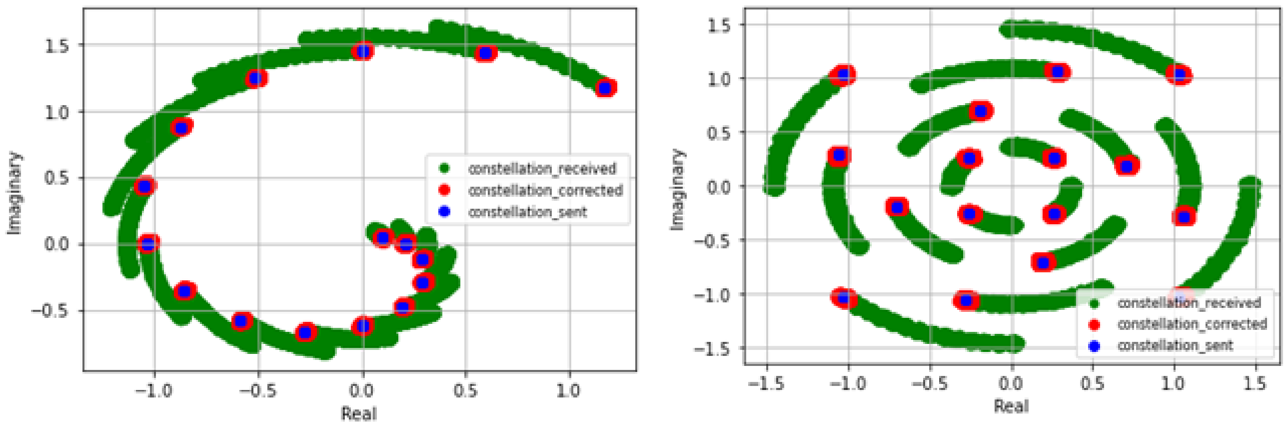

Figure 5-2: 16-Spiral and 16-PC constellation sent, received, and corrected.

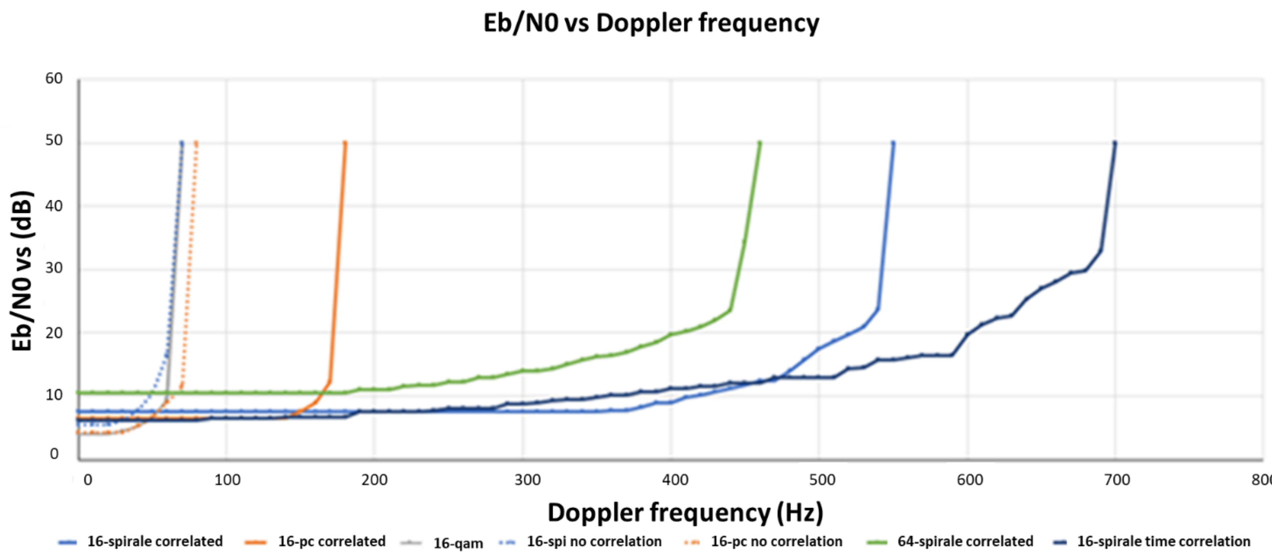

Figure 5-3 Evaluation against Doppler.

Description: The goal of polar constellation design is to create a constellation with one point per amplitude. Since each point is associated with a unique amplitude, the constellation is invariant in phase. This design leads to an infinity of solutions to define the constellation. Figure 52 represents the 16-spiral constellation, which is robust to PN but not to additive white Gaussian noise (AWGN). Another constellation is also proposed, namely, (16-PC), which is less robust to PN but provides a better behaviour against AWGN.

To build the spiral constellation the following equation is used

$$c(i) = a_i e^{(j\varphi_i)}, \tag{5-3}$$

with $a_i$and $\varphi_i$the amplitude and the phase of the I point respectively.

The CPE can be estimated with the following formula

$$\Delta_\varphi = \frac{1}{N}\sum_{i=1}^{N} \Delta_\varphi(i), \tag{5-4}$$

wherein N is the number of OFDM carriers used to estimate the phase variations.

Use Cases: The proposed constellation is related to energy-optimized services use case, mainly for implementing low-cost electronics and precise oscillators. The goal is to avoid increasing the cost of electronics and then develop algorithm to compensate this lack.

KPI/KVI: The system will be evaluated in terms of BER versus SNR and in terms of service continuity, especially comparing BER polar performance with QAM constellation as a reference. Doppler performance will be investigated, calculating the SNR needed to achieve a certain BER by increasing the Doppler shift.

Benchmarks: 5G-based environment is assumed, using classic 5G QAM with CP-OFDM and LDPC channel coding. First, AWGN channel and Doppler shift are used to validate the communication chain, but the goal is to test the system on different and more realistic THz propagation channels (with Doppler spread).

Assumptions: At first, CP-OFDM with LDPC combined with polar and QAM constellations affected by AWGN and Doppler shift will be as a basis of the developed link level simulations.

5.4 Learned MIMO waveforms

By utilizing end-to-end learning, it is possible to obtain waveforms which facilitate completely pilotless detection at the receiver side. This will enhance the spectral efficiency, especially in MIMO scenarios where pilot overhead is fundamental. This work is an extension of the earlier end-to-end learning where only single-antenna transmissions were considered. Here, the aim is to address the need to be able to operate with standardized waveforms. In particular, an OFDM system is considered, where a learned constellation shape is utilized to facilitate blind MIMO detection with a DeepRx-type convolutional neural network (CNN)-based receiver [HKH21]. The receiver takes in the Fourier transformed received signal and outputs the log-likelihood ratios (LLRs) for each spatial stream. Further details of the scheme are provided in Section 6.3.1.

6 Intelligent radio air interface

This chapter covers AI/ML-driven air interface design mainly based on the contributions from Task T4.4. AI/ML-driven air interface design refers to the use of AI and ML techniques in the design and optimization of wireless communication air interfaces. The AI/ML-driven air interface design approach learns single or multiple functionalities at either the transmitter side, or the receiver side, or both the transmitter and the receiver sides of a communication system to optimize specific objectives. By incorporating AI/ML into air interface design, wireless communication systems can benefit from higher flexibility, increased efficiency, improved performance, and enhanced adaptability to the changing network and environment conditions [MBR+22].

The chapter discusses intelligent transmitter, covering AI/ML-based MIMO transmission, beamforming, antenna selection, user selection for MU-MIMO, and resource allocation. It also explores AI/ML-based waveform design and coded modulation optimization. Additionally, intelligent receiver is presented, including AI/ML-based functionalities at the receiver including power amplifier non-linearity compensation and CSI acquisition, involving CSI prediction and compression. Lastly, the chapter addresses optimization methods for functionalities at both transmitter and receiver sides, such as CSI feedback, channel encoding and decoding, and MU-MIMO optimization.

6.1 Intelligent transmitter

This section presents enablers for intelligent transmitters which use AI/ML capability at the transmitter side for single or multiple functionalities. This section covers AI/ML-based techniques for MIMO transmission, flexible waveform, and optimized coded modulation design.

6.1.1 MIMO transmission

This section covers AI/ML-based enablers for MIMO transmission schemes including beamforming, antenna selection, multi-user paining for MU-MIMO transmission, and resource allocation for D-MIMO transmission.

6.1.1.1 ML-based beamforming with imperfect CSI estimates

CSI estimates are subject to imperfections since wireless channels are subject to variations and are unpredictable due to the factors such as fading, interference, and multipath propagation. When performing precoding in a wireless system, it is important to take imperfect CSI estimates into consideration to handle variations in the wireless channel without significant performance degradation. This is particularly important in dynamic environments, where the channel conditions can change rapidly. These problems are amplified for MU-MIMO systems where slight imperfections in the CSI estimates can lead to significantly increased inter-user interference and degraded system performance [LJ21].

Description: This work aims to develop AI/ML-based beamforming in the presence of imperfect CSI estimates. Considering that the channel estimation is performed using limited resources (in time, frequency or space), various estimation/prediction/extrapolation errors may occur. In the cases, where there is a model and CSI error has Gaussian distribution, the beamforming problem can typically be solved quite well using classical methods. However, when there is no such a model or errors are non-Gaussian the problem becomes more difficult to solve using classical methods. For example, in the case of channel aging, the errors may not follow a Gaussian distribution. Hence, methods based on AI/ML approaches can be applied to address the problem of beamforming in the presence of imperfect CSI. It is primarily intended for FR1 but can be extended to FR2 as well. This technique enables beamforming robust to imperfect CSI estimates for MIMO transmissions. In the proposed method, the CSI is fed to a trainable block (ML Beamformer) that outputs precoders based on imperfect CSI estimates (Estimated channels) and associated uncertainties (Estimated uncertainties). Training is done using gradient descent through a differentiable critic (Evaluator) to maximize a given performance metric (such as spectral efficiency). The performance metric is computed for the precoders from the ML beamformer given the true channels.

Use cases: By improving spectral efficiency, the proposed enabler for MU-MIMO transmission can be beneficial in use cases and services with high-capacity demand, such as the "Immersive smart city" use case, where a very high number of users and devices must be served simultaneously, or in the most data-hungry services envisioned in the "E-health for all" and "Fully merged cyber-physical worlds" use cases. The enabler can be also beneficial in "Energy-optimized services" by reducing the need for radio resources for CSI acquisition. The use case "Interacting and cooperative mobile robots" can benefit from the enabler due to the reduced retransmissions and hence lower transmission delay.

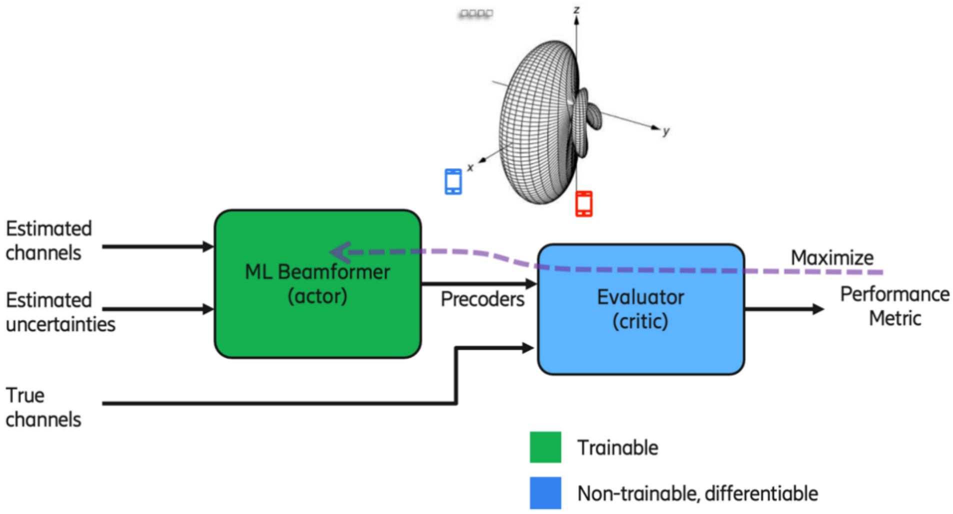

Figure 6-1 Schematic diagram outlining the training of an AI/ML-based beamformer in the presence of imperfect CSI estimates.

KPIs/KVIs: The proposed method is expected to reduce retransmissions, reduce worst case latency, reduce resources needs for CSI acquisition, and improve spectral efficiency.

Benchmark: The evaluation for beamforming with perfect CSI can be considered upper-bound, and the evaluation for classical beamforming subject to CSI imperfections (non-AI/ML) can be treated as the lower bound on the performance for benchmarking the proposed method.

Assumptions: Optimization is performed given a known structure of the MIMO receiver. Also, the training is done offline, so the true channel is assumed to be known.

6.1.1.2 Antenna muting / antenna selection

Massive multiple-input and multiple-output is a major driver to meet the high throughput requirements in the next-generation cellular networks. But the large antenna arrays employed to achieve the throughput goals come at the expense of high energy requirements. From a network operation perspective, it has been identified that shutting down/muting a certain part of the antenna array assists in maintaining the energy expenditure while not taking a hit in the delivered throughput [HWW+18].

Description: In this work considers downlink operation optimization of a base station antenna array in case of low load conditions. In a fully loaded system, all RF chains and antenna elements transmit with the maximum allowed power. The focus in this work is on the system at low load conditions and intend to reduce the number of RF chains and antenna elements, i.e., identifying the set of antennas muting patterns, which allow to achieve the target spectral efficiency with the lowest possible number of active antenna elements and RF chains. Thus, the spectral efficiency is maximized subject to transmit power constraints. This work will focus on sub-6 GHz band but will be applicable to other frequency bands as well. The problem being combinatorial in nature, and the intention is to identify neural network based low-complexity heuristics to achieve the set goals.

Use cases: Will allow energy saving in any use case where the system operates a part of the time below full load, where adaptation of antenna pattern is feasible while guaranteeing a minimum service performance for the active users. Most benefits are expected in outdoor macro deployments or where traffic load shows high variations, like the "immersive smart city" use case, but also "fully merged cyber physical worlds" or "e-health".

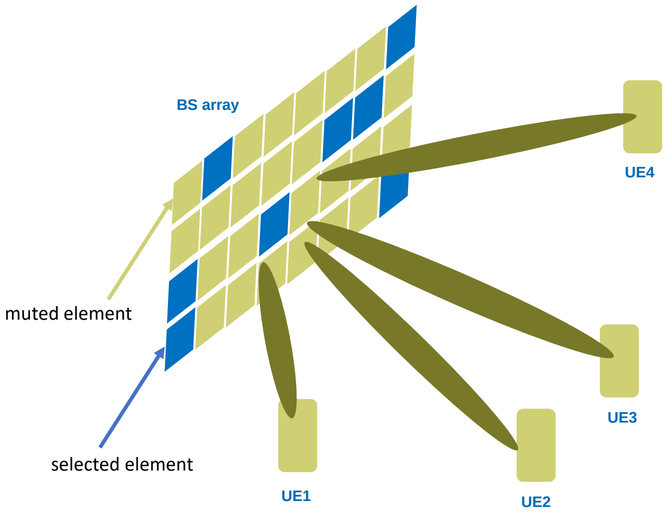

Figure 6-2 Principle of antenna element selection providing target spectra efficiency with maximized energy efficiency

KPIs/KVIs: Energy consumption reduction vs reduced system load, compared to energy consumption of reduced load with full array size.

Benchmark: Improvement in energy consumption compared to the performance of the baseline approach of [HWW+18].

Assumptions: The proposed solution assumes that the base station has knowledge of the UEs' traffic distribution and the SINR values. This will reduce overall power consumption and improve energy efficiency.

6.1.1.3 AI based MU-MIMO user pairing in limited feedback scenarios

MU-MIMO is a wireless communication technology that enables multiple users to simultaneously transmit and receive data over the same time and frequency resources, exploiting multiple antennas at the transmitter and receivers (see Figure 6-3). It is a key feature in 5G networks and their evolution, as it is used to increase network capacity and improve data rates for multiple users. A key issue in providing MU-MIMO is to properly group UEs that should be served simultaneously: only users with compatible channel characteristics should be grouped together (into so-called clusters), to avoid that the inter-user interference among concurrent users could reduce the quality of the received signals, neglecting the advantage of MU-MIMO transmission. The task is particularly challenging when the channel characteristics associated with each UE are not fully known at the base station (i.e., no full CSI is available), but only a partial amount of information is available (i.e., only partial CSI is available).

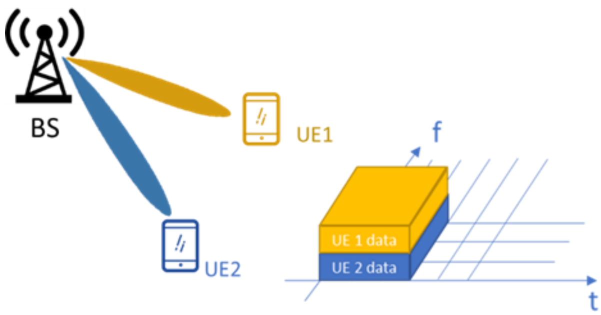

Figure 6-3 Example of MU-MIMO transmission sharing the same frequency and time resources between 2 users

Description: The proposed enabler exploits ML to select the UEs that can be co-scheduled in MU-MIMO, based only on partial channel information (e.g., channel quality indicator (CQI), precoding matrix indicator - PMI). This can be beneficial either in a frequency division duplexing (FDD) scenario, or in a distributed scenario where the full channel matrix of served UEs cannot be provided in the network element running the pairing algorithm. It is proposed to use a reinforcement learning (RL) approach [MKS+13] [BJ19] to select which users should be paired in MU-MIMO transmission.

Use cases: By improving network capacity and average user throughput, MU-MIMO can be beneficial in use cases and services with high-capacity demand, such as the "Immersive smart city" use case, where a very high number of users and devices must be served in parallel, or in the most data-hungry services envisioned in the "E-health for all" and "Fully merged cyber-physical worlds" use cases.

KPIs/KVIs: The most relevant KPIs are cell capacity (measured as spectral efficiency) and user throughput.

Benchmark: Performance of the proposed solution can be benchmarked against existing solutions exploiting traditional MU-MIMO approaches that exploit full channel knowledge such as Zero Forcing [SSH04] or Signal to leak and noise ratio (SLNR) minimization [TSS05]. As a lower bound, capacity and throughput obtained with single user MIMO can also be considered.

Assumptions: the solution assumes the availability of a Channel Quality Indicator reports provided by the UEs, as well as the availability of a codebook of possible precoding matrices against which a Precoding Matrix Indicator can be computed by the UE and reported to the Base station.

6.1.1.4 D-MIMO resource allocation

D-MIMO, or cell-free massive MIMO utilises geographically distributed multiple access points (APs) connected to a central processing unit to serve the users in the network using the same time-frequency resources. This novel distributed architecture is shown to provide more uniform spectral efficiency, enhanced coverage area, and connection robustness to the users. However, the increased number of antennas in the system increases the computational complexity and overheads in solving the optimisation problems using conventional optimisation-based or heuristic algorithms. Furthermore, sub-optimality of the solutions to non-convex problems, lack of flexibility, and parameter sensitivity in conventional resource allocation and optimisation algorithms also limit the performance of conventional approaches.

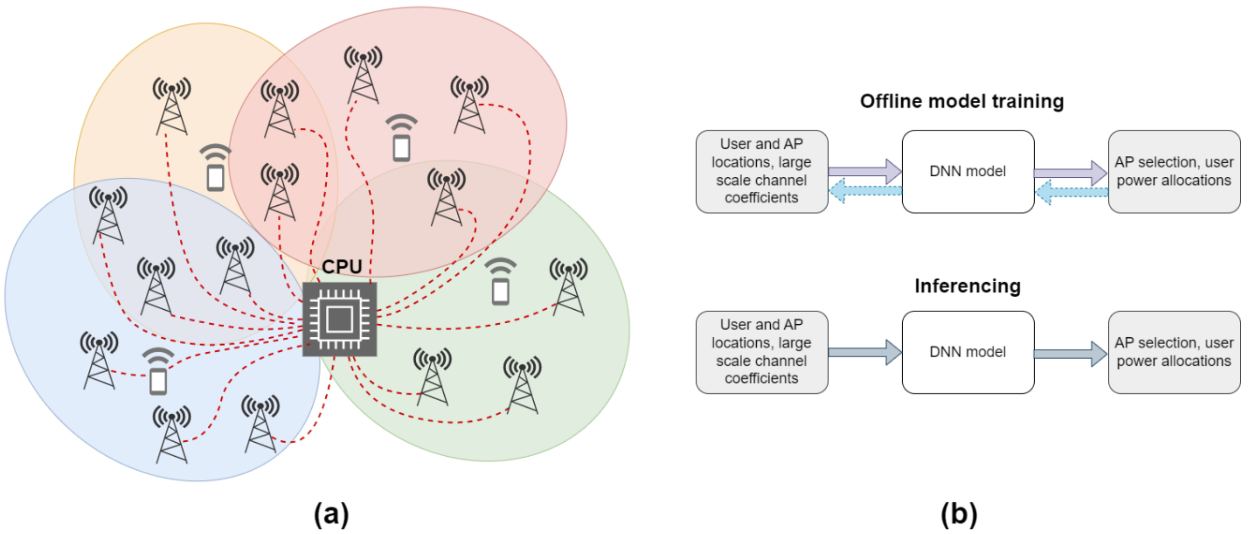

Figure 6-4: (a) User-centric D-MIMO architecture with AP selection. (b) ML-based AP selection and user power control approach.

Description: This enabler plans to use ML to address the above-mentioned issues associated with the conventional algorithms for D-MIMO resource allocation and optimisation. In [RMR+21] an unsupervised learning-based low-complexity power control algorithm for cell-free massive MIMO is proposed where a deep neural network is trained to learn user power allocations by directly optimising over the sum rate objective. The unsupervised learning algorithm is further extended to solve joint optimisation tasks in [RMR+23]. Both studies considered a full cell-free architecture where all the users are served by all the access points in the network which is not scalable in practice. Therefore, in this technical enabler, an AP selection mechanism to select the best set of APs to serve each user in the network to enable scalable implementation, improve energy efficiency, and reduce signalling overheads will be considered. Specifically, an ML-based low-complexity algorithm will be designed and developed for power control and/or beamforming optimisation along with AP selection. Furthermore, the effect of mobility on channel aging, pilot design and channel estimation, and formation of serving clusters will also be investigated.

Use cases: Immersive smart cities and fully merged cyber-physical worlds are potential use-cases where the D-MIMO architectures can play a role in achieving reliable connectivity, higher data rates, and improved coverage.

KPIs/KVIs: Relevant performance metrices for the proposed enabler are throughput and computational complexity.

Benchmark: The performance of the proposed solutions can be benchmarked against conventional optimisation-based/heuristic algorithms for the resource allocation and optimisation problem. Specifically, the computational complexity and user throughputs will be evaluated in comparison with the performance from conventional algorithms.

Assumptions: The solutions assume control signalling and other required D-MIMO architectural components to be in place. Furthermore, centralized processing is assumed where the proposed algorithm is implemented in the central processing unit which is connected to all the access points in the network. Also, it is assumed that ideal synchronisation is there between the access points.

6.1.2 New flexible multicarrier waveform

Multicarrier modulations (typ. CP-OFDM) have established themselves in various standards thanks to their advantages compared to the single-carrier system: robustness against multiple paths, simple equalization, and natural association with MIMO systems, etc. But there are still areas for improvement such as resistance to Doppler, out-of-band radiation, PAPR, etc.

Description: One new flexible waveform, called adaptive multicarrier modulation (AMCM), which has the advantages of OFDM as well as the spectral quality of OQAM (filtered multicarrier without cyclic prefix) is proposed. This new type of multicarrier modulation is flexible in terms of environment adaptations (propagation channel, Doppler and channelization). Flexibility is possible by changing one parameter in the waveform design formula (R parameter depicts in Figure 6-5) that adapts the system design and the waveform shape to the environment. Indeed, the waveform will be chosen by optimizing the interference that occurs between OFDM symbols and also the out-of-band radiations reduction (channelization impact) as illustrated in Figure 6-6.

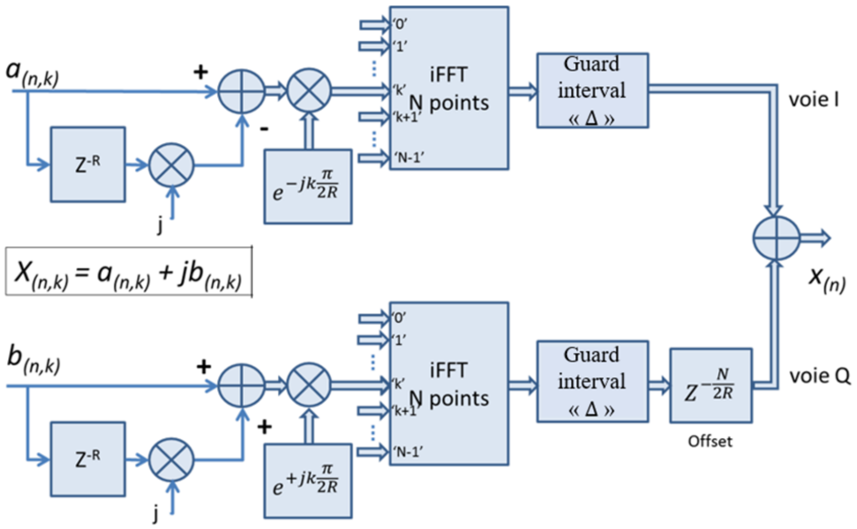

Figure 6-5 :AMCM Scheme

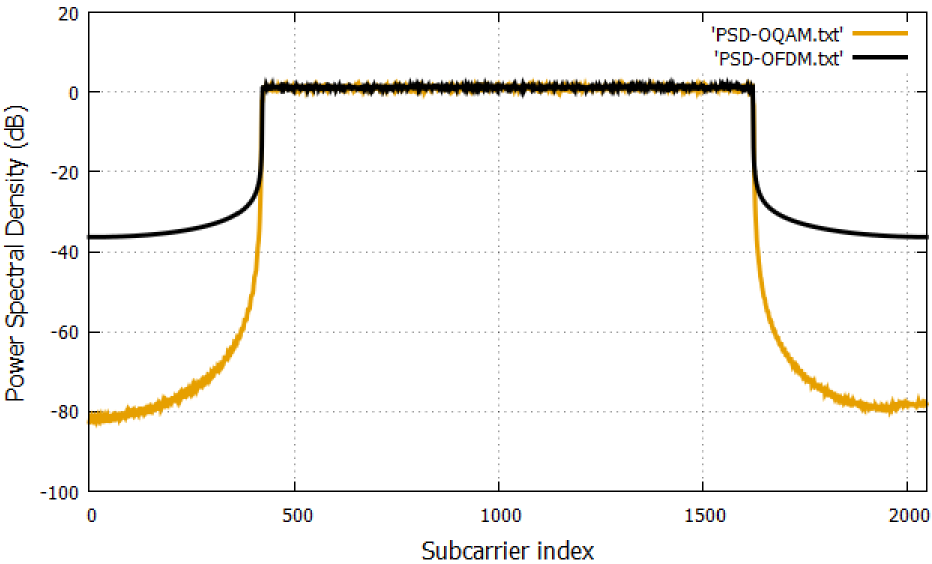

Figure 6-6: PSD OFDM vs OQAM

Use cases: Energy-optimized services such as network trade-offs for minimized environmental impact and use of small bandwidth channelization.

KPIs/KVIs: Power spectral density of the new shape compared to OFDM, resistance to multipath declined by better BER performance compared (BER vs SNR) to a waveform of filtered OFDM such as OQAM (Offset Quadrature Amplitude Modulation) [LAB95] [SSL02].

Benchmark: Link performance on 5G channel with multipath and Doppler shift.

6.1.3 Optimized coded modulation

Currently most of the existing communications systems consider the coding and modulation blocks to be separate. The binary bit stream is encoded via either LDPC or polar code, depending on whether the information block is longer or shorter in a general sense. Coded modulation, on the other hand, combines higher order modulation with channel coding for achieving higher spectral efficiencies. Combined coding and modulation were used in trellis coded modulation (TCM), in bandlimited scenarios [Ung82]. Given the research in index modulation, there were some attempts to consider a trellis coded spatial modulation [MRH+10]. Another direction is the consideration of a fixed QAM constellation being currently used in mobile communication systems – whether this can be modified to provide better performance, taking impairments into account with less overhead. The use of AI/ML methods to investigate these is quite interesting [RSR+23], especially given the new sequence to sequence mapping transformer-based networks [SRR+23]. There is also the source coding aspect in context-based communications such as text/image/video/task-oriented scenarios, considering the semantic information transmission. While segmentation of images has long been considered obtaining semantically coded information, the optimal transmission in a wireless environment is still ongoing research especially in the case of video [LGR+23]. Bit interleaved coded modulation (BICM) is a well-studied area in coded modulation for achieving higher spectral efficiencies [CTB98]. Delayed BICM (DBICM) further improves the performance by the added memory from the delaying which provides additional information at the receiver [MLY+16]. Recently, spatial modulation (SM) has drawn increased attention as a special case of index modulation along with BICM and DBICM showing improved BER performance [LDZ+23].

Description: The main objective in this work is to consider coded modulation as an integral entity, specifically in DBICM, making use of AI/ML and/or other intelligent algorithm-based approaches to facilitate better learning and optimisation. The aim is to further improve the performance of delayed bit-interleaved coded spatial modulation (DBICSM) proposed in [LDZ+23], by optimising different components of the system. To this end, different DBICM delay patterns that improve the DBICSM system will be investigated, along with suitable bit selection mechanisms for spatial modulation. Furthermore, the bit-channel capacities in DBICSM which vary due to unequal error protection (UEP) are to be optimised via appropriate LDPC code design [LQY21]. The initial investigations would assume ideal transmitters and receivers which will then be extended to include hardware impairments, imperfect channel state information at the transmitter (CSIT)/channel state information at the receiver (CSIR) etc., depending on the performance of the developed algorithms. Figure 6-7 illustrates the system model of a DBICSM system in which different blocks will be optimised depending on a selected metric such as the bit-channel capacity.

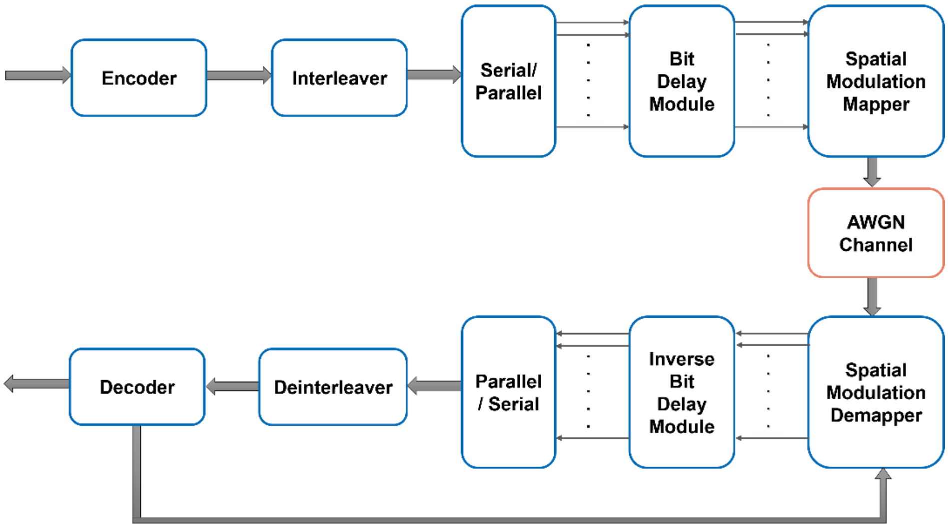

Figure 6-7: System model of an example delayed bit-interleaved coded spatial modulation (DBICSM) system.

Use cases: Immersive smart cities

KPIs/KVIs: FER, BER, Energy efficiency

Benchmark: Can be benchmarked against standard coding and modulation-based links as used in 5G systems. Complexity and performance are the main criteria for comparison.

Assumptions: CSIT and CSIR are initially assumed to be available. These are expected to be relaxed as the research progresses. This is applicable for both single carrier and multi-carrier transmissions.

6.2 Intelligent receiver

This section presents enablers for intelligent receiver in which AI/ML-based techniques are used for single or multiple functionalities including AI/ML-based compensation of PA non-linearity, and AI/ML-based CSI acquisition techniques.

6.2.1 Power amplifier non-linearity compensation

Non-linearity of wireless transceivers, specifically PA (Power Amplifier) hardware imperfections, could pose major limitations towards having high throughput, and cost and energy efficient wireless communication systems. Such limitations from PA are typically compensated in the transmitter, e.g., by applying power back-off or performing digital pre-distortion (DPD) aiming to linearize the transmitter. However, applying PA power back-off leads to lower energy efficiency, and lower output power, and hence lower coverage; and performing DPD results in higher complexity of the transmitters.

Description: To this end, a receiver technique using ANN (Artificial Neural Networks) demapper was suggested to compensate for the PA non-linearity in the receiver side, when DFT-s-OFDM (Discrete Fourier Transform – spread-OFDM) signal transmission was considered [FHS23], and for compensating phase noise in [FS20]. The receiver performs channel estimation using reference signals and conducts equalization using the estimated channel state information. The proposed ANN demapper performs per resource element soft bit de-mapping of the received signal before the channel decoder.

The study in [FHS23] was limited to lower frequencies and lower bandwidths for a single antenna setup. Next generation of wireless communication is expected to operate in higher frequencies using larger bandwidths and multiple antennas. Power added efficiency and linearity of PA in higher frequencies are generally lower than those operating in lower frequencies. Memory impacts of PA operating in higher bandwidth may be considerable as well. Additionally, in band distortion created by PA in higher frequencies may become a bottleneck for transmission.

Additionally, when the PA hardware imperfection is present, there may be more potential in considering an ANN demapper that performs soft bit de-mapping over several resource elements to compensate inter-carrier interference. The block diagram of such an AI-empowered receiver is shown in Figure 6-8.

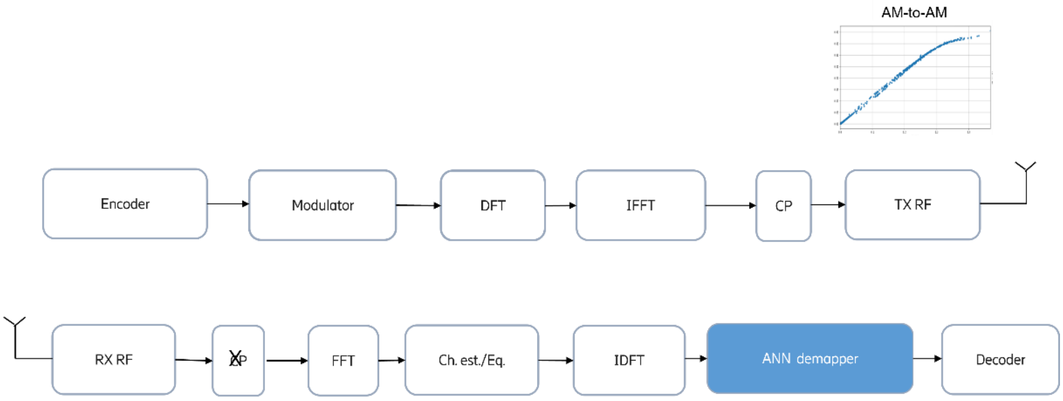

Figure 6-8: AI-empowered receiver

Use cases: By improving spectral efficiency, the proposed enabler for can be beneficial in use cases and services with high-capacity demand, such as the "Immersive smart city" use case, where a very high number of users and devices must be served simultaneously, or in the most data-hungry services envisioned in the "Fully merged cyber-physical worlds" use case. The enabler can be beneficial for the "E-health for all" use case by enhancing energy efficiency of medical IoT devices and can be also beneficial in the "Energy-optimized services" use case by enabling transmitters to operate in more non-linear hence energy efficiency operating point. The use case "Interacting and cooperative mobile robots" can benefit from the enabler due to the enhanced reliability and hence reduced retransmissions and lower transmission delay.

KPIs/KVIs: The performance metrics that will be considered for evaluation include uncoded BER, BLER, spectral efficiency, energy efficiency, and throughput.

Benchmark: To present the merits of the solution, link level simulation will be performed to compare the performance of the AI-empowered receiver against a legacy receiver with conventional demapper in the presence of PA hardware imperfections and the legacy receiver in presence of linear PA. It will be shown that proposed method can compensate the impact of distortion and increase throughput or extend the coverage of the communication link.

Assumptions: The proposed enabler required the model to be trained offline based on collected labelled training data, where the labelled training data includes the received signals and the corresponding transmitted bits.

6.2.2 AI-enabled CSI acquisition

6.2.2.1 AI/ML -based CSI prediction

CSI prediction is introduced in [RFP+23] as one of the enablers for the next generation of mobile networks. In FDD systems, the CSI feedback imposes high feedback overhead, thus motivating the study of ML-based CSI feedback enhancements. The autoencoder (AE)-based CSI compression has been possible implementation option for the ML-based CSI feedback enhancement use cases in the new Release-18 study. The schematic diagram of Release-18 CSI enhancement based on CSI-compression is illustrated in Figure 6-9 below. As can be seen in the figure, the AE-based CSI compression aims to minimize signal overhead or reconstruction error through dimensionality reduction, but it is prone to performance degradation due to channel aging in a dynamic network. To avoid the channel aging issue of AE-based CSI feedback enhancements, the aim is to develop an ML-driven solution that allows accurate predictions of radio channel variations in time by using the 3GPP CSI feedback mechanism.

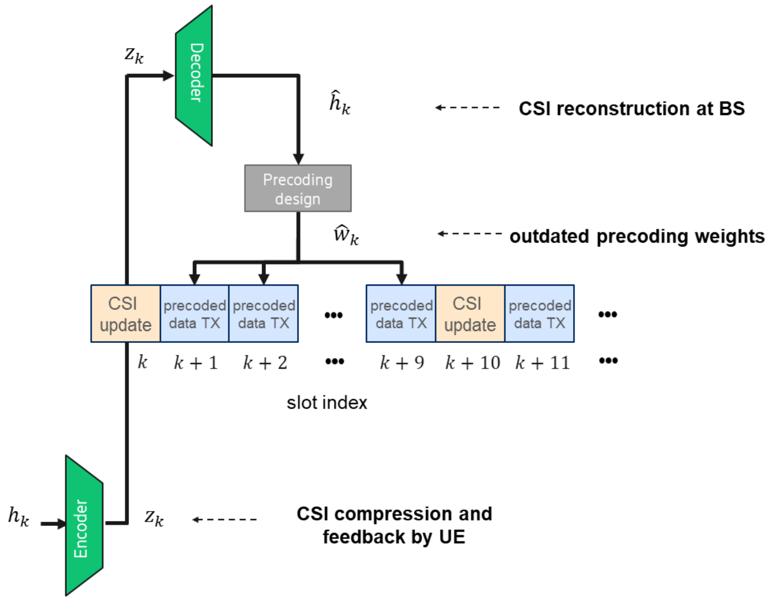

Figure 6-9 Schematic diagram of feedback-based precoding design in FDD systems under the assumption of AE-based CSI compression that has been investigated in Release-18, 3GPP.

Description: The main objective is to propose a predictive CSI framework that learns temporal dynamics of radio channel for prediction applications. Formulating the channel prediction problem as an image prediction problem in the temporal-frequency domain, the framework deploys deep neural networks, which have proven to be very efficient for a broad range of computer vision problems, to identify dynamic representations from radio channel images. The dynamics representation has the potential to enable a recursive multi-step-ahead prediction that provides an accurate multi-step ahead prediction model under 3GPP CSI feedback mechanism.

Use cases: by improving spectral efficiency, the proposed enabler can be beneficial in use cases and services with high-capacity demand, such as the "Immersive smart city" use case, where a very high number of users and devices must be served simultaneously, or in the most data-hungry services envisioned in the "E-health for all" and "Fully merged cyber-physical worlds" use cases. The enabler can be also beneficial in "Energy-optimized services" by reducing the need for radio resources for CSI acquisition. The use case "Interacting and cooperative mobile robots" can benefit from the enabler due to the reduced retransmissions and hence lower transmission delay. The enabler would be beneficial for the "Digital twins for manufacturing" by providing capability to predict CSI and perform actions in advance.

KPIs/KVIs: the proposed enabler is expected to improve BLER and throughput.

Benchmark: The upper bound for the performance of the proposed enabler is the one with the genie-aided perfect CSI, and the lower bound is one for the Release-18 CSI compression.

Assumptions: CSI prediction and performance evaluation under the baseline assumptions as in the release-18 CSI compression study, basically applying 3GPP CSI feedback mechanism with new CSI RS patterns and signalling for explicit CSI feedback.

6.3 Intelligent transmitter and receiver

This section presents AI/ML-based enablers for joint transmitter and receiver design where AI/ML-based methods are used in both transmitter and receiver to perform functionalities. The models at the transmitter and receiver can be designed jointly.

6.3.1 Learned MIMO waveforms

Prior works have already shown the benefits that can be obtained by learning jointly the waveform and the receiver processing. Herein, such end-to-end learning is considered as a foundation for a truly AI-native air interface, where the transmitters and receivers can learn to operate in the most efficient manner over the air. One of the main challenges with such an approach is in dealing with various practical limitations, such as the need to standardize the waveforms as well as to be able to support spatial multiplexing with MIMO arrays.

Description: The main objective is to extend the SISO E2E learning approach presented in [HEX23-D43] to support spatial multiplexing with multiple antennas, while also addressing the need to be able to operate with standardized waveforms. The considered system model is presented on a high level in Figure 6-10. In particular, an OFDM system is assumed, where a learned constellation shape is utilized to facilitate blind MIMO detection with a DeepRx-type CNN-based receiver [HKH21]. The receiver takes in the Fourier transformed received signal and outputs the LLRs for each spatial stream.

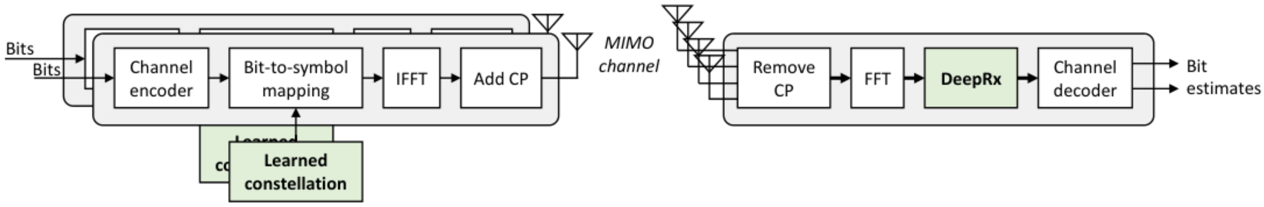

Figure 6-10: The considered end-to-end link model, where the green colouring highlights the elements which are learned.

To achieve pilotless spatial multiplexing, individual constellations for each transmitted spatial stream are learned jointly with DeepRx, using binary cross entropy at the receiver output as the loss function. The training is performed end-to-end from the transmitter to the receiver, considering the non-learned transmitter and receiver processing, as well as the impact of the wireless channel and noise. Such a scheme will be able to communicate over a MIMO channel with higher spectral efficiency, as all resources can be used for data transmission. A crucial aspect of the proposed scheme is the constellation shapes, which must be separable at the receiver side without using any prior channel knowledge. One approach is to define pre-learned constellations for different channel conditions and use-cases, which ensures that no spectral resources need to be wasted on over-the-air (OTA) training. This is applicable also to the SISO scenario where blind detection is done based on the constellation shape, although no spatial multiplexing is performed.

Use cases: Since the main target of the proposed approach is to improve throughput and/or spectral efficiency, this enabler is beneficial for most use cases. However, the most benefits are of course obtained with those use cases that involve transferring large volumes of data over the air. This means the most relevant use cases are “Fully merged cyber-physical worlds”, “Immersive smart cities” and “E-health for all”.

KPIs/KVIs: The primary targeted KPI is increased spectral efficiency and throughput, by reducing overhead and in some cases BLER. As for the KVIs, this work is mainly addressing trustworthiness via increased integrity of the physical layer transmission, and sustainability via aiming for a more efficient air interface.

Benchmark: The comparisons are carried out against 5G demodulation reference signal (DMRS)-based conventional system, where no ML components are utilized in the physical layer.

Assumptions: It is assumed that the different radio devices have ML hardware capable of inferencing the pre-trained models in real time.

6.3.2 AI-based CSI feedback

6.3.2.1 CSI feedback

CSI feedback is a key element to enable MIMO and beamforming techniques and improve system performance. However, as the number of antenna elements increases the CSI overhead becomes significant. While codebook-based channel state feedback (CSF) can limit overhead, this is at the expense of a degraded CSI accuracy. The planned contribution is a demo (the details of the framework are given in Section 10.1.1) to show that cooperative AI-based techniques can improve the spectral efficiency and accuracy of CSF compared to legacy CSI schemes.

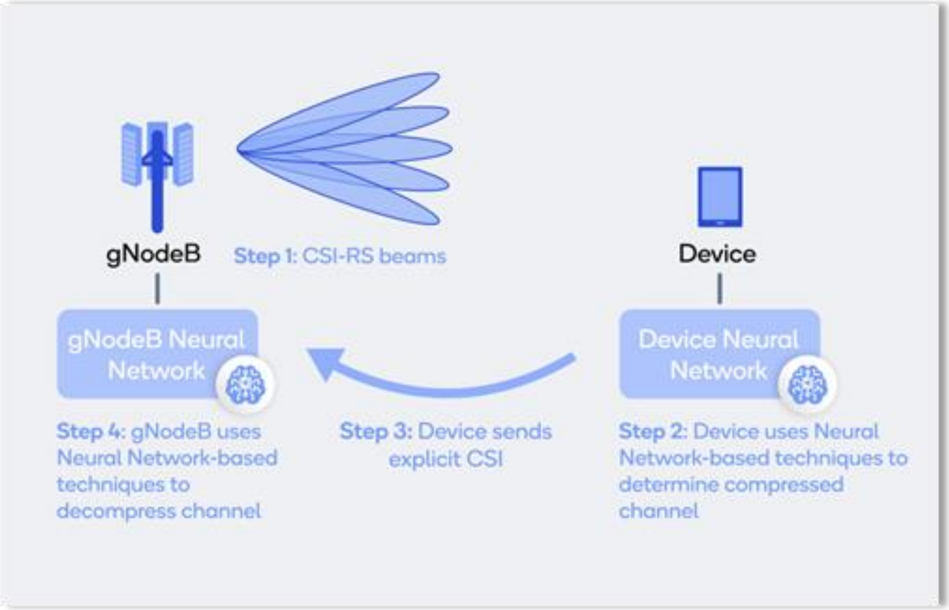

Figure 6-11 Overview of the AI-based CSF architecture.

Description: In this demo, an AI algorithm runs at the Device to encode/compress the CSI to be sent. At the gNB a reciprocal AI-based technique decompresses the CSI. Together, those two AI algorithms can improve CSI resolution for a given number of bits, or equivalently reduce overhead for a fixed CSI resolution, with no performance loss compared to legacy schemes (Type I, Type II, or eType II CSF). This demo demonstrates cross-vendor cooperation to enable joint AI solutions without each party revealing their proprietary AI/ML design, as described in Section 10.1.1.

Use cases: The proposed contribution enables higher spectral efficiency and increased channel state feedback accuracy. As such, this contribution can be beneficial to use cases that require high-capacity communications such as “Fully merged cyber-physical worlds” where enhanced quality of experience for mixed reality and holographic applications and devices is required; and to the “Digital twins for manufacturing” use case where reliable and low-latency communications are needed to guarantee seamless user experience. In some scenario (e.g., low mobility) this contribution may be beneficial for “Energy-optimized services” by reducing power consumption thanks to a lower number of transmit bits (reducing overhead) for CSF and by extending UE sleep duration due to higher spectral efficiency. In addition, the increased CSI accuracy combined with beamforming techniques would benefit the “E-health for all” use case by extending service accessibility thanks to increased coverage.

KPIs/KVIs: The proposed contribution enables a reduction in the number of bits for transmitting CSI (KPI: overhead reduction or improving spectral efficiency, KVI: Sustainability) and higher reliability thanks to improved CSF resolution (KPI: accuracy, KVI: Trustworthiness).

Considered Performance Metric: The CSI accuracy of the proposed AI-based will be evaluated by measuring the squared generalized cosine similarity (SGCS) loss of the input channel state eigenvector versus the (compressed at UE then decompressed at gNB) eigenvector of the estimate channel state at gNB.

Assumptions: Massive MIMO, FR1 band and TDD mode. It is assumed that devices have ML processing capability.

6.3.2.2 CSI compression

Precoding is an important modern tool to “solidify” the original physical communication channel $\boldsymbol{H}$. This is done by means of a precoder matrix $\boldsymbol{W}$, that maps the data symbols onto the transmit antennas, such that the effective channel $\boldsymbol{H}_{\text{eff}} = \boldsymbol{HW}$ delivers better performance. For the DL precoding, the base station (BS) combines the channels from its multiple transmit (TX) antennas toward single or several receive (RX) antennas at the

UE in a beneficial way, performing phase and/or amplitude synchronization, providing larger RX power gain. Precoding is a wide field with Linear and Non-linear precoders applied to the MU-MIMO (for which channel pseudo-inverse or more advanced techniques are used) and a single-user MIMO (SU-MIMO) (for which the TX maximum ratio combining (MRC), singular value decomposition (SVD) Telatar precoders, or Finite Alphabet precoders in some sense approximating them are used) [VP07].

To know how to perform channel "synchronization" that varies in frequency and time, the BS (still considering the DL case example) needs to know the channel. Exchange of CSI within a communication system provides information about the channel quality (affected by fading, multipath propagation, and interference from other signals), and can be exploited to design the precoding matrix. When the BS cannot know the channel to perform such channel solidification (e.g., learn channel via reciprocity in TDD mode), it can get CSI information from UE. In addition, as part of CSI, information about beneficial precoder to be used can be sent in the form of PMI. Various PMI schemes have been adopted into standardized precoding techniques [ATM19]. Generally, CSI data can be large and complex, making it challenging to process and store. To overcome these challenges, various CSI compression techniques have been developed to reduce the size of the CSI data while preserving its essential information, including vector quantization, principal component analysis, and neural network-based approaches [GWJ+22]. An important question is how to compress the PMI size and still deliver a good precoder toward the BS.

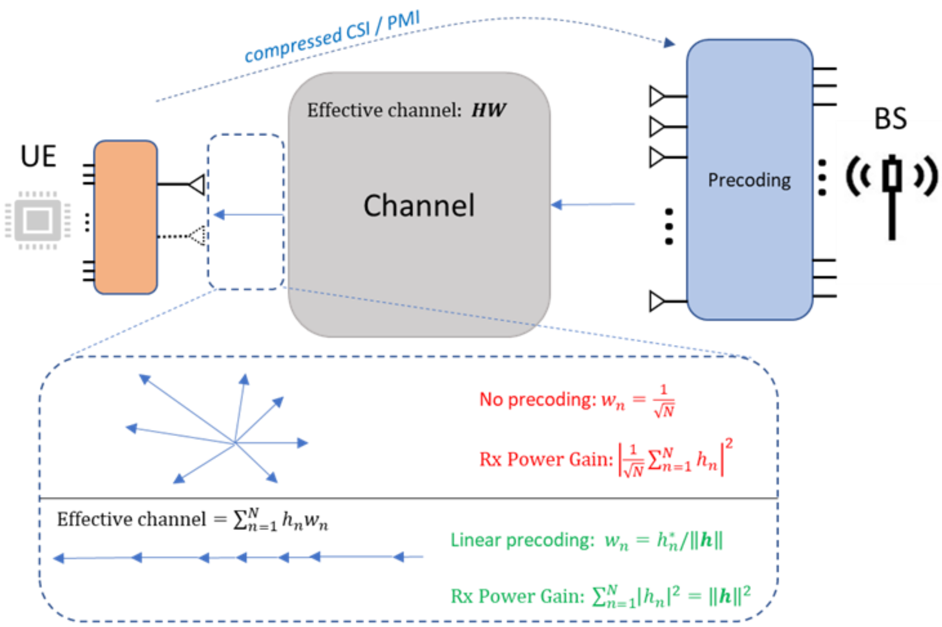

Figure 6-12 Example of SU-MIMO channel improvement via linear precoding under unit TX power constraint.

Description: In this work, the focus will be mostly on the SU-MIMO case and Linear precoders for real-world implementations in low-capability devices. The aim is to analyse and develop advanced methods for combined CSI precoding and compression that preserve the system performance and improve the physical channel while helping the network adapt quickly to changing environment. Design and optimization of practical standardized schemes will be investigated together with AI-enabled schemes and compression of feedback information that can keep processing complexity and signalling overhead at reasonable levels.

Use cases: The advanced CSI precoding and compression enabler targets at preserve the performance and average user data rates for low-capability devices. Thus, it can be beneficial to IoT-relevant services with very high number of smart devices served in parallel and high total capacity demand, such as services that can arise within "Immersive smart city" and "E-health for all" use cases.

KPIs/KVIs: Precoding can be used to improve the performance of the system (optimize the data transmission rate, improve the system efficiency, and reduce the error rate) by reducing interference and increasing the

SNR. The proposed methods are expected to provide improvements towards those directions, i.e., improve SNR gain with reasonable complexity and resource usage.

Benchmarks: Theoretical lower and upper bounds will be considered as well as 5G standardized precoders such as Type1 and enhanced Type2 (eType2). BLER curves will be produced to identify SNR gaps from already established techniques and theoretical optimal (but extremely complex for practical implementation) approaches.

Assumptions: Several standard channels (e.g., TDLA-30-5/LOW) and channel estimation techniques will be considered. Low-capability devices will be of focus in this study (low max BW capability, low number of antennas, etc.)

6.3.3 Energy efficient LDPC channel encoding/decoding schemes

Error-correction codes are one of the essential functions of the digital communication chain. LDPC codes have been selected by 3GPP for 5G [38.212], as they offer a wide variety of size and code rate. A new structure which improves the performance according to the number of iterations of the decoder allowing to decrease the energy consumption of the system, is proposed.

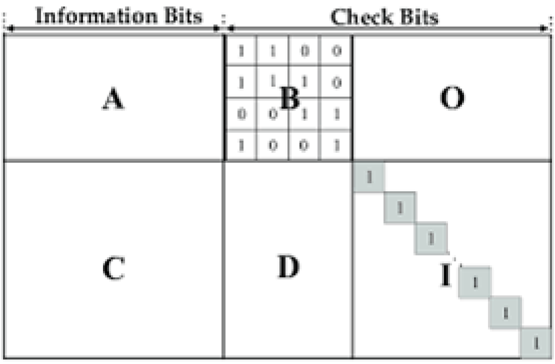

Figure 6-13 Scheme of LDPC-5G matrices.

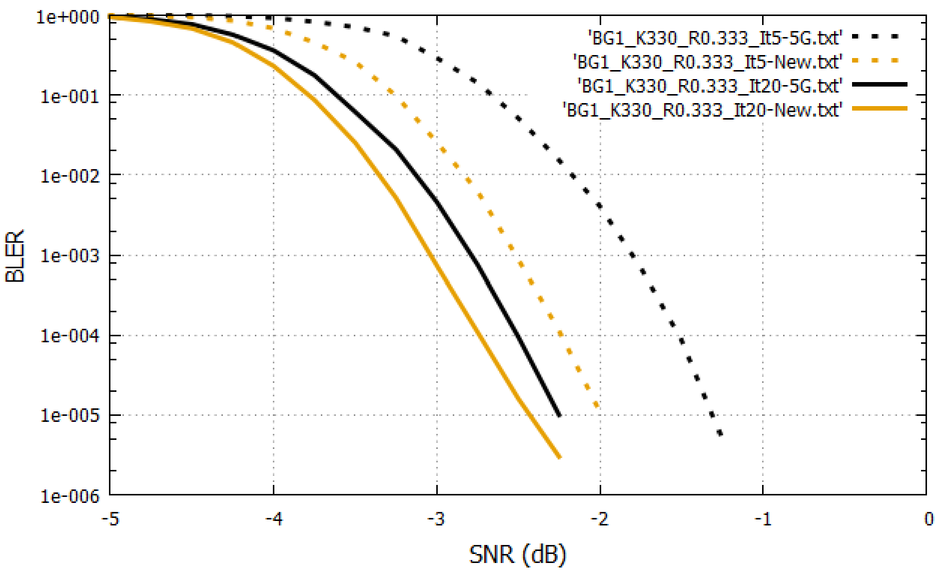

Figure 6-14: LDPC Performance BLER vs SNR (5 and 20 iterations).

Description: In the first phase, a new design for the 5G LDPC matrix is proposed which retains the constraints of the matrices defined by the 3GPP (cf. **Figure 6-13**) and which offers increased performance with a lower number of iterations (cf. **Figure 6-14**).

In a second step, new matrix design will be proposed for the design of 6G systems, improving performance while minimizing the hardware complexity and reducing energy consumption (optimization of the number of decoding iterations). AI/ML will be considered as one tool to achieve these goals by optimizing jointly the coding and decoding schemes.

Use cases: short packets for URLLC and also long packets sizes for eMBB use-cases are considered. The main objective being to explore energy-optimized services such as Network trade-offs for minimized environmental impact. All 6G use-cases can be addressed by this new LDPC design as short and long block packets sizes are considered.

KPIs/KVIs: Performance evaluation, BLER versus SNR, for different sizes and coding rate and comparisons between structures of current 5G-LDPC arrays versus newly determined arrays. Relative evaluation of the energy reduction of the proposed solution related to the number of decoding iterations.

Benchmark: Performance comparison between current 5G-LDPCs and new matrices in terms of BLER versus SNR for different code sizes and code rates on AWGN channel Using Min-Sum decoding algorithms as defined in [CYL+14].

Assumptions: The first hypothesis to evaluate the new matrices design are to retain the same structure (packet block sizes and coding rates) defined by the 3GPP and subsequently to propose a new structure for 6G for the matrixes definition.

6.3.4 MU-MIMO optimization in diverse device scenarios

MU-MIMO is a key tool for increasing the capacity of cell or user groups, using multiple antennas at both the transmitter and receiver, and allowing multiple users to access simultaneously the same channel. Several studies have investigated (and continue to investigate) MU-MIMO systems, even for massive amount of UEs, to evaluate performance under different algorithms and assumptions regarding, e.g., power allocation, beamforming, channel modelling. Main challenges of downlink MU-MIMO include the channel knowledge and its update, the communication with different users in a way that reduces or eliminates interference among them, as well as the complexity (both hardware and computational) originating from multiple antennas and implementation of MU-MIMO schemes [PSS+04] [SSH04] [AHA+21]. These specific challenges will be significantly augmented in expected 6G deployments of ~10 devices per m^2, where a BS will have to concurrently deal with several UEs of diverse architecture (antenna number, hybrid analogue-digital array architecture, BW capability, etc.) and a vast amount of user antennas in total.

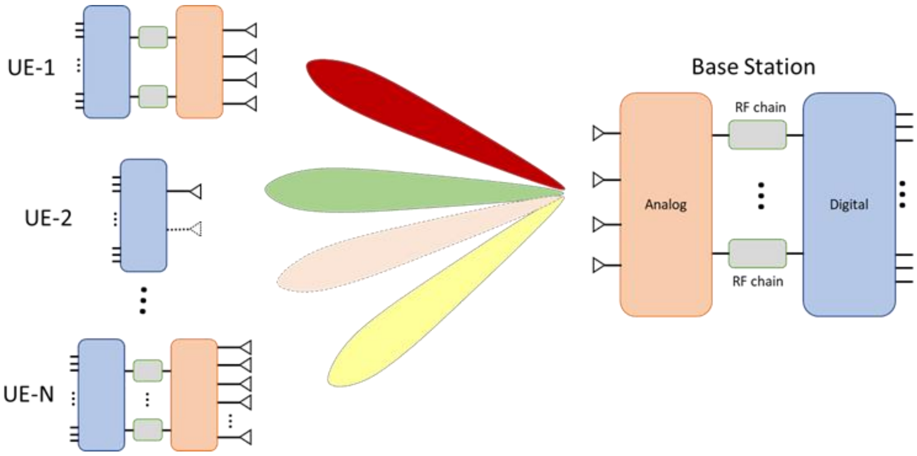

Figure 6-15 MU-MIMO optimization in diverse device scenarios.

Description: This work will primarily focus on the downlink case and will investigate MU-MIMO optimization methods, also employing AI, for scenarios with massive number of devices of diverse architecture, where the number of BS antennas is much smaller than the total number of the antennas on the UE devices. In that case, the full optimization of all MU-MIMO scheme parameters (e.g., precoding, channel estimation, feedback, etc.) may be prohibitively difficult and computationally intensive. Thus, trade-offs will be investigated, such as what can be done to deliver required performance but also to reduce the computational cost (and related energy consumption) on the Base Station and UE sides. Intelligence at the receiver side can help on the optimization of the channel estimation and respective feedback preparation, while intelligence at the transmitter side can help on the MU-MIMO precoder construction and optimization. It is also planned to look at some basic problems of such scenario: e.g., how to incorporate devices with large number of antenna elements and escape their pollution by multi-user interference, how to extend the range of the communication with the UEs in the MU-MIMO mode, how to reduce the response and adaptation times, etc.

Use cases: This enabler targets at optimizing performance in dense 6G scenarios where “typical devices” of high performance but also latency- and cost- optimized devices will coexist. Thus, it can be beneficial to services with very high number of various devices served in parallel and with high total capacity demand, such as services that can arise within “Immersive smart city”, “E-health for all”, and “Digital twins for manufacturing” use cases.

KPIs/KVIs: MU-MIMO can be used to improve the spectral efficiency of the system. Simulation results and respective analysis will be performed to identify trade-offs with computational complexity or energy efficiency and the influence of degrees of freedom will also be studied.

Benchmark: Theoretical bounds lower and upper bounds of different schemes and parameters will be considered for benchmarking the optimization analysis (downlink case will be of main focus). Comparison may be performed with techniques historically developed for MU-MIMO with specific device architectures (e.g., single/low antenna number) [PSS+04] [SSH04] [AHA+21]. Several standard channels (e.g., 3GPP 5G channels) and channel estimation techniques will be considered, as well as 6G possible frequencies and bandwidths (when respective channels will be available).

Assumptions: Simultaneous communication of massive number of antennas from UE devices with a lower number of BS antennas. Availability of control signalling provided by the UEs to BS, such as CQI and PMI reports. UEs with various antenna arrays architectures (e.g., fully digital, or hybrid analogue-digital).

7 MIMO transmissions

This chapter discusses MIMO transmission schemes for different frequency bands as part of the contributions from Tasks T4.2 on THz techniques and T4.4 on FR1 and FR2 techniques. Novel MIMO architectures, i.e., massive MIMO, D-MIMO, and RIS, are fundamental to deploying 6G. These schemes will improve the performance of communications systems by providing a more reliable link and higher throughput with spectral and energy efficiency. Hence, in this chapter, the contributions are divided into three categories: D-MIMO transmission, massive MIMO architectures, and RIS-assisted transmission schemes.

In Section 7.1, the contributions discuss D-MIMO coherent and non-coherent transmission by providing link-level performance analysis. Another study approaches the scalability issue due to the increased number of users served by a single processing unit. In this case, an AI/ML -based selection method is proposed to achieve a scalable transmission. Furthermore, the performance of centralized massive MIMO and D-MIMO systems is explored in an indoor industrial scenario for machine-type communication (MTC). Next, cooperative beamforming design is investigated for decentralized transmissions by performing bi-directional training. Other contributions analyse location-dependent coded-caching for MIMO systems, EMF exposure of distributed transmissions at 3.5 GHz, and full digital MIMO architecture for sub-THz frequencies. The massive MIMO section proposes hybrid analogue-digital architectures and fully digital architectures to assist sub-THz communication scenarios. Finally, the RIS section considers multiple implementations regarding signal level analysis and control procedures for indoor and outdoor RIS integration. Other contributions include RIS-assisted D-MIMO system, channel estimation for vehicular communications and integration of reflecting modulation to RIS-assisted systems.

7.1 D-MIMO schemes and architectures

This section covers D-MIMO for the different frequency ranges currently used in 5G and the specific aspect for each frequency range. The section presents transmission schemes including coherent joint transmission, non-coherent joint transmission, and specific D-MIMO schemes.

7.1.1 Coherent joint transmission

This section addresses coherent joint transmission schemes for D-MIMO transmission.

7.1.1.1 Distributed-MIMO with analogue fronthaul

Generally, D-MIMO networks perform better than conventional co-located systems in terms of throughput and coverage, however new challenges arise due to additional requirements on bandwidth, synchronization, and/or power consumption [IBN+19], thus novel solutions are needed to realize the potential of D-MIMO in a cost-effective manner. To take full advantage of the diversity and power gains of D-MIMO networks, i.e., coherent joint transmissions (CJTs) from two or more transmit/receive points (TRxPs), stringent synchronization requirements including phase stability with sub-nanosecond precision must be met. A feasible solution to realize CJTs is to use analogue fronthaul links in combination with centralized processing and RF carriers' generation. Analogue radio-over-fibre (ARoF) and analogue free-space optics (AFSO) links are an alternative that can fulfil the preceding requirements facilitating the deployment of D-MIMO networks. ARoF and AFSO links have been proven to fulfil the 3rd Generation Partnership Project (3GPP) [POD+22], [PHJ+23], RF mandatory error vector magnitude (EVM) and adjacent channel leakage power ratio (ACLR) transmitter requirements for the frequency range 1 (FR1) [38.104], validating analogue fronthaul links as a feasible solution for future deployments such as D-MIMO.

Description: In D-MIMO, multiple antennas are positioned at various locations throughout a network, such as different base stations or access points. These antennas can work synchronously and coherently to enhance the performance of the network. In a D-MIMO network with centralized processing, the TRxPs can be connected via wired or wireless fronthaul links [JRS22]. Depending on the deployment characteristics and needs, the length of these links is different, and this difference may span from few to hundreds of meters adding delays in the transmission from each TRxPs. To fulfil CJT requirements, fronthaul links delays must be considered for synchronization and phase stability with sub-nanosecond precision must be ensured, however, with conventional digital fronthaul interfaces, this is challenging to achieve. Thus, if the different TRxPs are not fully synchronized and their transmissions are not phase aligned, it is often the case that only non-CJT (NCJT) is feasible. Analogue fronthaul is a feasible solution for D-MIMO fronthaul as channel estimation includes the phase and amplitude changes caused by both the wired path (i.e., fronthaul link) and wireless path of each TRxP. ARoF and AFSO fronthaul links technology does not use bits to transmit information since the optical carriers that propagate through a medium are modulated with RF signals.

KPIs/KVIs: BER. Transmitter RF minimum requirements: signal quality (in terms of EVM requirements) and out-of-band emissions (in terms of ACLR requirements) [38.104].

Benchmark: Theoretical diversity and power gains in a D-MIMO network. The received SNR can be expressed as [TV05]:

$$\mathrm{SNR} = \frac{\mathrm{P}\|\mathbf{h}\|^2}{\mathrm{N_0}} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \frac{\mathrm{p_i}|\mathrm{h_i}|^2}{\mathrm{N_0}} \quad \textbf{(7-1)}$$

where $h = [h1, h2, \dots, hN]$ is the $1 \times N$ channel vector, N_0 is the noise power spectral density, and p_i is the average transmit power per TRxP.

Assumptions: D-MIMO centralized processing and TDD duplexing method. In addition, for simplicity in experimental work, simplified OFDM signals are considered, e.g., no control channel.

7.1.1.2 D-MIMO performance evaluation at the link-level

Massive MIMO is a physical-layer wireless technology that has allowed 5G to reach such good performances in term of throughput. One limitation in such deployment is the quality of service of cell-edge users due to inter-cell interference. One way to tackle this interference is to use joint transmission coordinated multi-point (JT-CoMP) which enables coherent transmission from cluster of BSs.

Because greater throughput is needed in today's applications, higher bandwidth is required. To find such resource, higher carrier frequency is used. This leads to a new problem: communication reliability. Indeed, higher in frequency means higher pathloss, lower available output power of semiconductors and most importantly phenomenon of **blockage** is worsened [CTT+16].

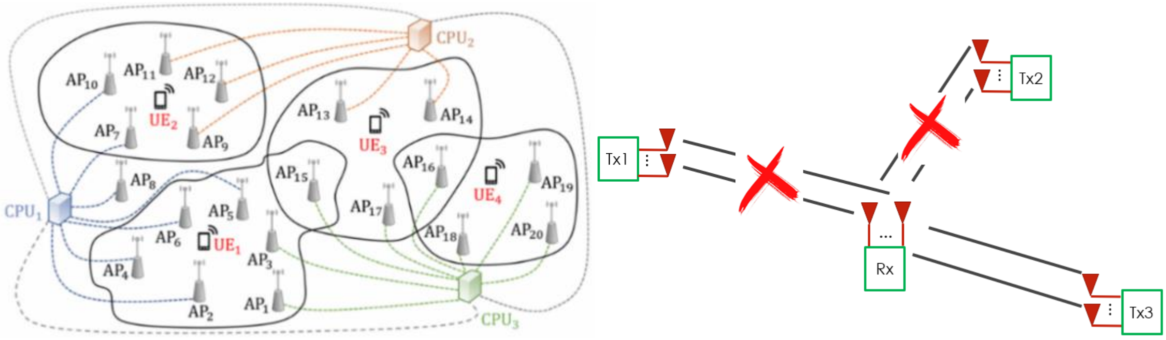

Figure 7-1 Example of cell-free massive MIMO (Left) and illustration of blockage (Right).

Description: Large scale D-MIMO also called cell-free massive MIMO is a technique using both aspects of JT-CoMP and massive MIMO. In fact, with D-MIMO the UE receives signals from multiple APs (similar to JT-CoMP). Moreover, with high-density deployment, the number of APs is large (similar to massive MIMO), however, the antennas in D-MIMO are distributed. The densification will reduce the likelihood of blockage in the context of mmWave.

Use cases: D-MIMO will be implemented in 3GPP scenarios (see [38.901]) like the Urban Micro for example. After the model will be adapted to the use cases defined in Section 2.3 like "Immersive smart cities" which represent typical environment in which the geographical distribution of antennas will improve the outage probability.

KPIs/KVIs: The objective is to offer innovative, scalable multi-antenna techniques adapted to the different 6G frequency bands. To do so, a 6G PHY-layer communication chain will be fully implemented using Python to obtain BER versus SNR at the output as discussed in Section 4.2.1 ("Link modelling of 6G physical layer"). The chain will implement coding, modulation, D-MIMO-OFDM technique with precoding to focus energy on UE direction. The main challenge will be the channel modelling in the THz frequencies through the choice of modelling blockage (time, blocker size, probability law). This will have a significant impact on the final performances when comparing D-MIMO with MIMO.

Benchmark: First, the chain will be validated using a known channel statistical model like Rayleigh fading one to be able to derive BER equation and check whether it matches with simulation. In another time, a more advanced channel is going to be added to bring it closer to reality. Of course, power normalization will be done for fairness.

Assumptions: To obtain performance evaluation, several assumptions are made: RF imperfections, power amplifiers nonlinearities, hardware impairments and PN are omitted. The evaluations will be done with FR2 frequencies.

7.1.2 Non-coherent joint transmission

In a distributed massive MIMO network, also known as cell-free massive MIMO, antennas (transmission reception points, TRPs, Radio Units, RUs) are geographically spread out over the area, in a well-planned or random fashion, as shown in Figure 7-2. RUs are connected to a Distributed Unit (DU, a.k.a. CPU) with baseband functionality through wired/wireless fronthaul links. Macro diversity provides the possibility for simultaneous connectivity to large number of tightly coordinated RUs, which will enable not only higher data rates and more uniform service level over the covered area, but also enhanced connectivity robustness, especially for mmWave/sub-THz operation.

3GPP has defined Coordinated Multi-Point (CoMP) schemes in LTE and 5G NR [36.741]: (i) non-coherent joint transmission (NC-JT Case 1), where different layers are transmitted across 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.

Most of the existing transmission techniques require instantaneous CSI to form precoders which can only be realized together with accurate and up-to-date channel knowledge. There may be unknown channels due to, e.g., high mobility, lack of uplink/downlink reciprocity, pilot contamination, where network can switch to a robust transmission mode can be preferred in such challenging conditions.

Description: As an application of NC-JT transmission scheme, orthogonal space-time-frequency block codes (STFBCs), 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. The focus will be on determining appropriate clustering of RUs and UEs, where each cluster can use a different orthogonal code, so that overall performance is optimized.

Use cases: D-MIMO will enable use-cases that would require limitless connectivity with very high rates everywhere and robust transmission covering high frequency bands as well. Immersive communications and fully merged cyber-physical worlds are potential use-cases where D-MIMO can play a role.

KPIs/KVIs: Outage probability and ergodic rates are planned to be studied.

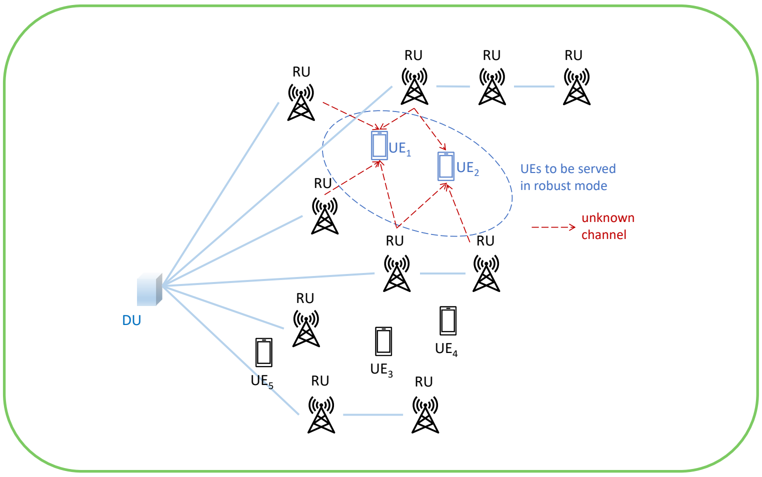

Figure 7-2 Robust D-MIMO transmission mode.

Benchmark: Potential performance gains over known techniques that can be used when the channel is not known will be shown and performance gaps to precoders making use of channel estimates will be identified. Small cell approach where inter-cell interference is not coordinated, SFN transmission (3GPP NC-JT Case 2b), and maximum ratio transmission (MRT) will be used as benchmark methods. It is expected that proposed method will perform better or close w.r.t. the baseline methods if proper clustering has been provided.

Assumptions: It is assumed that channel is constant within the coherence block, and channel estimation for multiple RU antennas is needed at UE side. Large codes require high fronthaul data traffic that would need small clusters and code sizes to limit fronthaul rates.

7.1.3 Scalable transmission

Due to its ability to considerably enhance communication performance, such as spectral efficiency, energy efficiency, etc., D-MIMO has gained increased attention as a crucial technique that may be used in 5G and beyond wireless communication. The implementation feasibility of D-MIMO, also known as cell-free MIMO, is one of the important challenges. In D-MIMO, it is generally assumed that all APs communicate to a single CPU to coordinate and process the signals of all UEs. As the number of served UEs increases, the complexity of communication networks increases dramatically. Therefore, such a D-MIMO strategy cannot support a large number of UEs, resulting in an unscalable D-MIMO system. In order to achieve such scalable transmission, the D-MIMO network can employ an advanced AI/ML-based selection method. A trained model with high generality is capable of selecting APs and UEs efficiently and effectively.

Description: To address the scalability issue of D-MIMO and satisfy the dynamic requirements, a fast and low complexity selection strategy is essential. However, the traditional selection strategies either rely on the mercy of nature (e.g., the random pilot assignment) or are high complexity algorithms without considering dynamic scenario requirements. In this project, this work will first illustrate the requirements and system network as a graph. Then the RL and graph neural network (GNN) will be used to colouring with a fixed number of colours. The colouring result will be helpful for the AP and UE selection strategy and optimize the resource allocation.

Use cases: This enabler relates to the Hexa-X-II use cases "Digital twin" and "Immersive smart cities". In immersive smart communities, a large number of IoT devices and sensors contribute to the construction of the network structure. Then, the proposed model of this enabler makes connectivity for such a mobility scenario reliable. Together with these sensors, it is able to satisfy the digital twin's requirements for a high data rate and minimal power consumption.
KPIs & KVIs: Throughput, and energy consumption
Benchmarks: The above KPIs/KVIs will be compared with the selection methods (e.g., random method, clustering based, localisation based, algorithms, etc.)
Assumption: The path loss map is known by the CPUs to help build the connection graphs; the number of required timeslots (the number of colours) should be given.

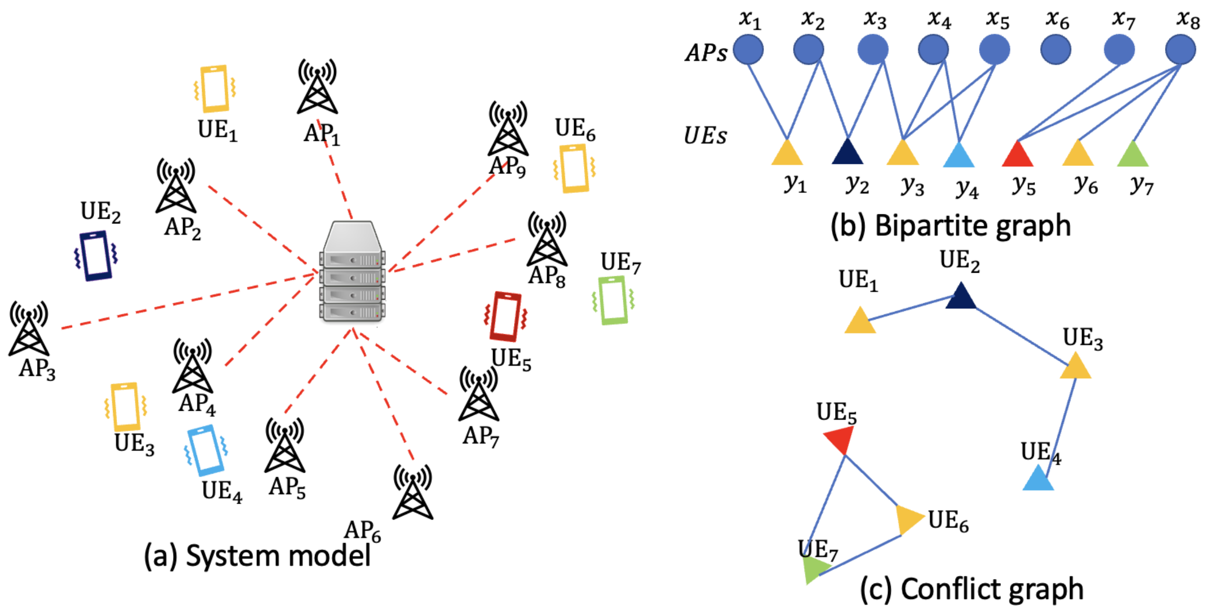

Figure 7-3 The D-MIMO system model and conflict graph with a viable colouring result.

7.1.4 Distributed massive MIMO for machine type communication

In addition to eMBB service category, which can be seen as the evolution of 4G for human-type communications applications such as mobile internet, 5G introduced native support for MTC in two broad categories: massive MTC (mMTC) and critical MTC (cMTC), also known as URLLC. The former aims at applications where data rate, latency and reliability requirements are low to moderate, but it is necessary to provide wireless connectivity to a massive number of low power and low complexity devices. The later focuses on applications with very stringent requirements in terms of latency and reliability, such as autonomous vehicles and critical factory automation. Current 5G networks are still not able to fully satisfy the requirements of cMTC and mMTC use cases, thus industry and academia have been working together on novel technical solutions for 6G networks aiming to meet them. One of the physical layer solutions that has been extensively studied is the evolution from centralized massive MIMO to distributed massive MIMO: instead of having a massive number of antenna elements collocated at a single BS, the coverage area is jointly served by several APs, each equipped with a single or few antenna elements.

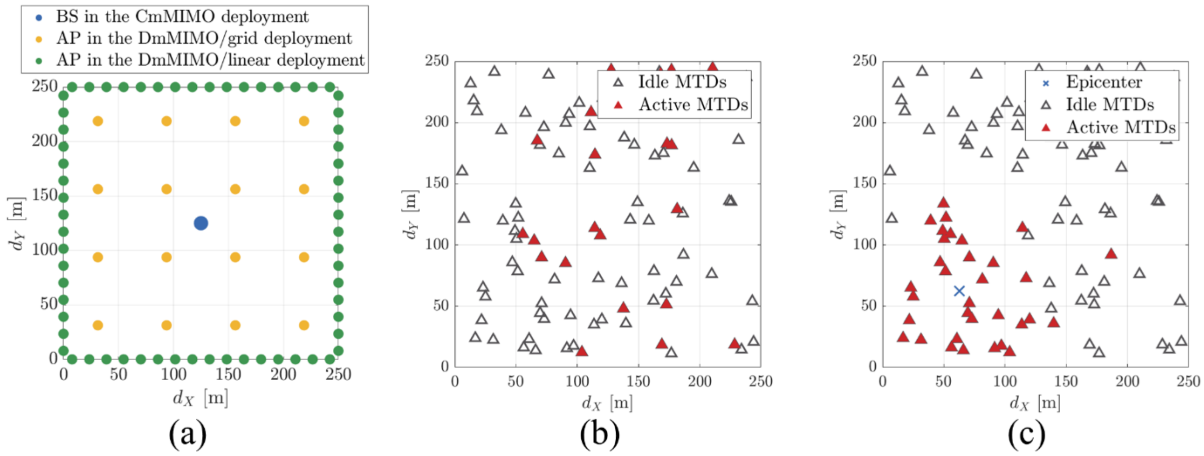

Figure 7-4 - (a) Illustrations of the different massive MIMO deployments compared in the indoor industrial scenario, (b) snapshot of the MTC network under regular traffic and (c) snapshot of the MTC network under alarm traffic.

Description: This work compares the uplink performance of centralized massive MIMO and different distributed massive MIMO setups in an indoor industrial scenario. Two different traffic models are considered for MTC: i) regular traffic, where the active devices are uniformly distributed in the coverage area, since they periodically transmit non-critical updates to the network, and ii) alarm traffic, where an alarm event occurs on the factory hall and triggers the activation of the devices located nearby. Given the occurrence of the alarm event, the probability of a device being triggered is given by an alarm triggering probability function, which considers the distance between the device and the epicenter of the event and the intensity of the event.
Use cases: This enabler aims at both cMTC and mMTC applications for indoor industrial scenarios, such as wireless sensor networks for process monitoring and critical factory control. These applications are related with the "Digital Twins for Manufacturing" use case.
KPIs: the target data rate is set for the uplink transmissions, and the *outage probability* of the different massive MIMO setups will be evaluated under the different MTC traffic models.
Benchmark: The numerical results show that, under the regular traffic, the distributed massive MIMO setups always outperform the centralized massive MIMO counterpart, which is aligned with the results from the literature. However, it is shown that, under alarm traffic, the centralized massive MIMO can present better performance than the distributed massive MIMO. Under the occurrence of an alarm event, a BS located at the center of the factory hall and equipped with many antenna elements can provide better connectivity to the network if the active devices are concentrated in a hotspot around the epicenter of the event.
Assumptions: The study adopt a channel model validated by 3GPP for indoor industrial scenarios that considers both small scale and large-scale fading. It is considered that all the devices transmit with the same fixed power in the uplink. It is assumed that all the APs are connected to a common CPU through perfect fronthaul connections. Perfect CSI is also assumed.

7.1.5 RIS-assisted integrated access and backhaul

The sub-urban integrated access and backhaul (IAB) networks have been impacted by the tree foliage on signal propagation. The attenuation and scattering of wireless signals caused by leaves and branches can lead to a considerable performance degradation in these networks. Consequently, it is of utmost importance for network designers and operators to adopt innovative strategies, cope with such issues, especially in maintaining reliable and sufficient data rates in the backhaul links. RISs due to their unique capabilities, can be helpful in bypassing the tree foliage affected direct backhaul links.

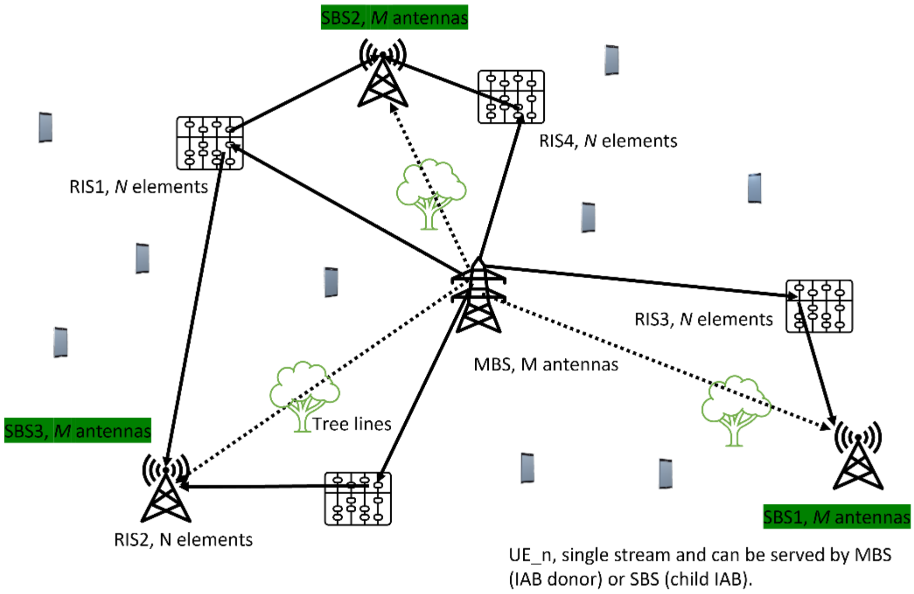

Figure 7-5 Illustration of RIS-assisted IAB scenario in the presence of tree foliage

Description & use cases: The work may optimize the network and address the tree foliage issue in IAB networks, for the sub-urban areas, focusing on the backhaul links. This aligns with the use case, "Immersive smart cities".
KPIs & KVIs: Service coverage probability, Backhaul rate and trustworthiness respectively.
Benchmarks: The above KPIs/KVIs may be compared with the MBS only, IAB only and RIS assisted IAB networks.

Assumption: It is assumed that only backhaul links are affected by the tree foliage. The path from MBS to RIS and RIS to SBS are LoS without tree foliage, i.e., only MBS-SBS direct link is affected by tree foliage.

7.1.6 Decentralized transmission

Cell-free massive MIMO is a promising technology that can improve spectral efficiency beyond traditional cellular networks. Unlike traditional cellular networks, cell-free massive MIMO involves all BSs in a given area that belong to the same operator serving all subscribed UEs, which reduces intercell interference and is ideal for small-cell applications. However, most literature on this technology has focused on non-cooperative beamforming strategies, in which each BS designs its own beamformer without exchanging CSI via backhaul links. However, recent studies have shown that cooperative beamforming strategies can achieve even greater performance gains.

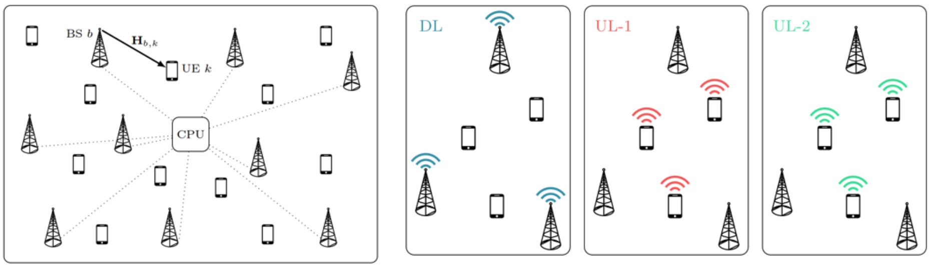

Figure 7-6 Cell-free massive MIMO (left). Single Bi-directional iteration consists a DL and two UL signals.

Description: The implementation of cooperating beamforming design requires a significant amount of CSI exchange between the BSs and/or the BSs and the CPU through backhaul links. Unfortunately, this approach can also introduce delays in the beamforming computation, which can be problematic. To overcome this challenge, a new OTA uplink signalling (UL-2) is introduced, which eliminates the need for backhaul signalling in cooperative beamforming design.

The proposed approach involves bi-directional training, where each iteration includes simultaneous pilot transmission by all BSs during the DL phase as shown in the above figure. After the UE receives these pilot signals, it computes its combiner. In the subsequent UL phase, all UEs concurrently transmit UL-1 and UL-2 signals as shown in the above figure. UL-1 comprises local UE channel information, while UL-2 contains the cross-channel information among the BSs [AGT21]. This information is crucial for computing or updating cooperative precoders at each BS. Upon receiving the UL-1 and UL-2 signals, each BS independently computes the cooperative precoder in parallel. During each bi-directional training iteration, the BS emits a DL signal to facilitate UE beamformer training, and the UE transmits uplink (UL-1 and UL-2) signals for BS (cooperative) beamformer training [AGT21]. Furthermore, the training resources can be optimized based on the system requirements [GAT22].

Use cases: The proposed method can be used for joint transmission and/or cell-free massive MIMO systems and is mostly applicable to small cells. This can be part of the ‘Fully merged cyber-physical worlds’ and the ‘Digital twins for manufacturing’.

KPIs/KVIs: Sum rate of the system and average rates of the UEs.

Benchmark: The above KPIs/KVIs are compared with the local beamforming designs such as local MMSE and conjugate beamforming.

Assumptions: It is assumed that the BSs and UEs are synchronized, and path delays are not considered. The simulations are performed under Rayleigh fading channel.

7.1.7 One-bit ADC for multi-cell setup

The next generation of wireless systems, beyond 5G, may operate at extremely high frequencies up to 1 THz, which requires larger antenna arrays and increasingly sharp beamforming to maintain a consistent signal-to-noise ratio. However, the ADCs/ DACs used in current systems consume a lot of power. One solution is to use low-resolution ADCs/DACs with 1 to 4 quantization bits to enable the use of massive MIMO arrays, which require hundreds or thousands of antennas. 1-bit ADCs/DACs are particularly appealing due to their minimal power consumption and simplicity. Additionally, the fully digital architectures can overcome limitations associated with hybrid analogue-digital beamforming at sub-THz frequencies.

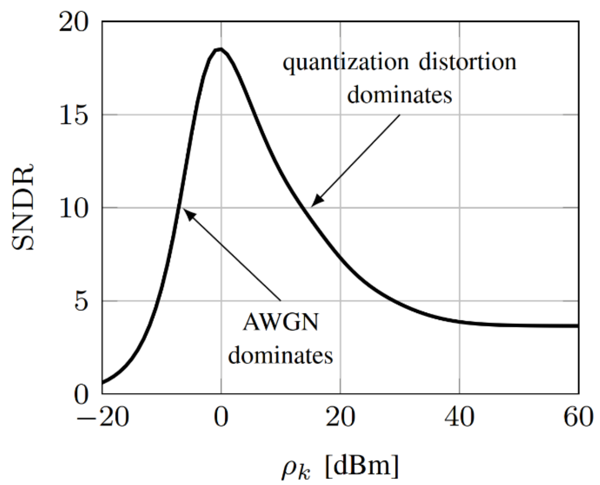

Figure 7-7 Fully digital 1-bit ADC system and the corresponding SNDR behaviour with respect to the UE transmit power.

Description: Fully digital 1-bit ADC architectures are attractive due to their minimal power consumption, but their performance in terms of for signal-to-noise and distortion ratio (SNRD) can be non-monotonic with respect to a UE transmit power, as illustrated in Figure 7-7. At low transmit powers, the performance suffers due to the AWGN whereas, at high transmit powers, the performance degrades due to quantization distortion. To achieve the optimal performance, the UEs must operate a specific power level, which requires power tuning [AT22]. This is particularly challenging in multi-cell and cell-free setups [AGT21], making it essential to develop algorithms that can tune the UE transmit power for optimal performance in both single-cell and multi-cell systems.

Use cases: Fully digital 1-bit ADC architectures can be employed in devices with low power consumption and high-frequency massive MIMO. This can be part of the 'Fully merged cyber-physical worlds' and the 'Digital twins for manufacturing'.

KPIs/KVIs: Higher sum rate, lower SER.

Benchmark: The performance of the power-tuned single-cell system will be compared to the system where UEs transmit at maximum power without power tuning. Additionally, the performance of the multi-cell system will be compared to that of the single-cell system.

Assumptions: Assuming perfect synchronization between BSs and UEs and neglecting any path delays or radio frequency impairments.

7.1.8 Multi-antenna Location-dependent coded caching

Caching frequently accessed content close to or at the end-users is a common solution to ensure fast and reliable content delivery in wireless networks. This is particularly relevant for upcoming data-intensive applications like XR, which rely heavily on asynchronous content reuse [MST22]. By proactively storing content for the end-users during off-peak hours, network congestion during busy periods can be reduced. Coded caching (CC) is an innovative approach to caching that uses aggregated memory across the entire network, instead of relying on individual users' caching capabilities. The CC scheme uses strategic cache placement and multicast delivery to achieve both local and global caching gains. This can lead to even better performance than traditional caching methods [MN14].

In real-life wireless communication scenarios, users often move around while receiving data from the server. This is especially true for dynamic applications like wireless XR, where users are immersed in a three-dimensional world and can interact with each other and the environment [MST22]. As users move around, their connectivity conditions change based on their location in the network coverage area. The traditional CC scheme assumes an error-free shared medium, which is not always feasible when dealing with dynamic wireless communication scenarios [MN14]. Rather, transmission schemes must account for the varying connectivity of wireless links to ensure efficient utilization of wireless resources. The optimal utilization of wireless resources requires a transmission scheme that adjusts the data rate for each user based on their current connectivity [MST22].

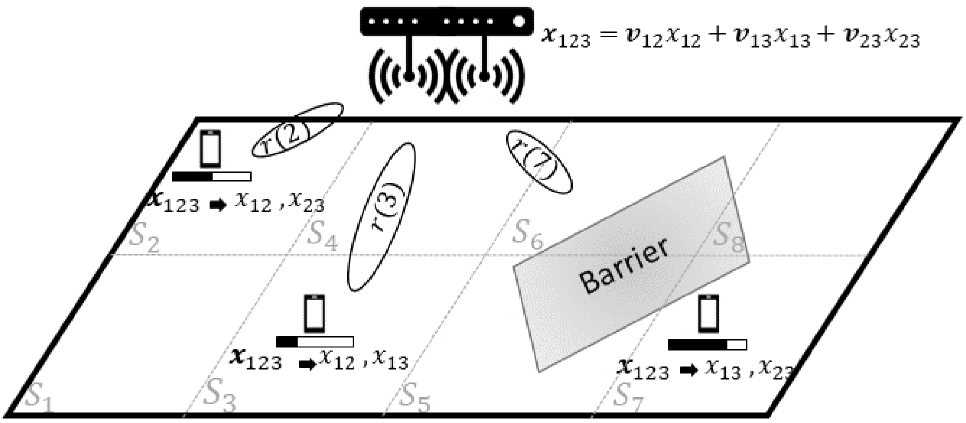

Figure 7-8: An application environment with 3 users, and 8 STUs. The black bar below each user shows the amount of cached data based and connectivity condition.

Description: This deliverable presents a novel multi-antenna CC-based content delivery scheme for location-dependent data requests, particularly focused on collaborative XR applications that require high data rates and are subject to strict delay constraints. This configuration is characterized by a single transmitter equipped with multiple antennas accessing a library and serving a group of cache-enabled users. The intended study considers a wireless connectivity scenario in which users are free to move and they request content based on where they are at any given moment within the application environment. As a specific use-case, it is assumed that a multi-user immersive viewing environment where a group of users is submerged in a network-enabled immersive application that runs on high-end eyewear. This corresponds to "Fully-merged cyber-physical worlds" and "merged reality game/work" use cases. Such a scenario entails a substantial volume of multimedia traffic with guaranteed QoS throughout the operating environment.

Using the proposed approach, an XR environment is considered, which is divided into single transmission units (STUs) as illustrated in Figure 7-8, each requiring a separate 3D omnidirectional image to reconstruct the virtual environment. Users request missing data from the server to reconstruct their field of view (FoV) in each STU. Once all user requests are collected, the server transmits the missing data to all users over the air, while also providing instructions on how to recreate their FoVs based on cache content and the delivered data. To accommodate the varying quality of wireless connectivity at different STUs, memory is allocated in a location-dependent, uneven manner based on the approximated or predicted data rate at each STU. This differs from the conventional CC schemes, where the same memory allocation is applied to all files in the library and requires entirely different delivery schemes to be developed. To address this, a novel packet generation scheme is introduced that creates packets with sizes proportional to uneven cache ratios. Finally, a multicast beamforming scheme is proposed with multi-rate support to leverage global caching and multiplexing gains simultaneously and improve QoS compared to existing approaches. Overall, the approach aims to efficiently deliver high data-rate connectivity with strict delay constraints for collaborative XR applications.

Use cases: The main use case is for fully merged cyber-physical worlds, including multi-user MR gaming, augmented virtual shopping, and non-material fashion, as well as distributed digital twins synchronization.

KPIs/KVIs: the relevant KPIs and KVIs are the high data rate and reliable transmissions.

Benchmark: This pertains to the utilization of traditional caching techniques where complete files are cached at various network entities. Additionally, conventional cache coordination methods that employ max-min-fairness (MMF) beamforming are being used as a baseline. With this scheme, higher transmission rates can be achieved within a bounded delivery time when compared to conventional CC schemes that utilize uniform cache placement.

Assumptions: Perfect channel knowledge, uniform location visit probability, centralized processing, simultaneous data request.

7.1.9 EMF evaluations for distributed transmissions

In traditional networks, adjacent radio units operating at the same frequency band usually do not transmit coherent signals, meaning that the EMF exposure contribution from multiple radio units should be combined in an uncorrelated way. In a D-MIMO deployment, each distributed radio unit is coordinated through a centralized unit with a dedicated antenna precoding scheme. Therefore, the EMF contribution from distributed radio units may need to be combined in a correlated way. For now, there is a lack of simulation tools to assess the combined EMF exposure from distributed radio units with phase coordination. An earlier work [Nyb22] developed the initial framework while a more comprehensive investigation is still required. The target is to develop a novel simulation scheme capable to accurately assess the EMF exposure in a D-MIMO deployment, considering different exposure metrics. The simulation scheme should allow the EMF exposure assessment to be performed for different antenna precoding schemes.

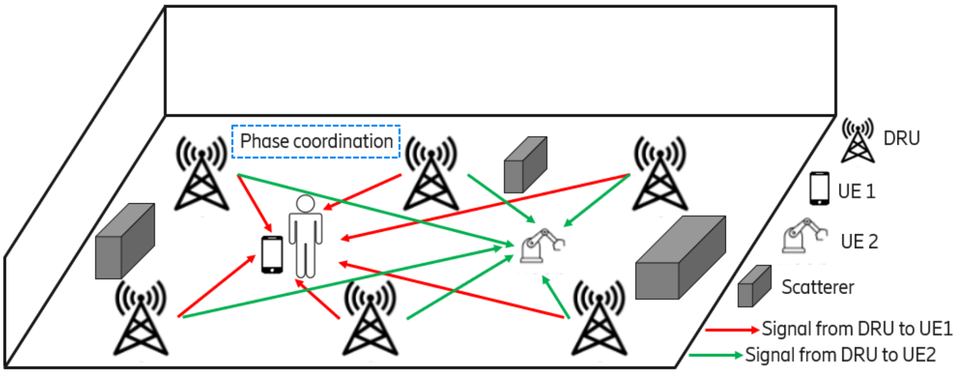

Figure 7-9: Schematic diagram of an indoor industrial environment with D-MIMO deployment serving two UEs. The signals from the DRUs towards the UEs generate a field distribution and therefore EMF exposure to people present in the environment.

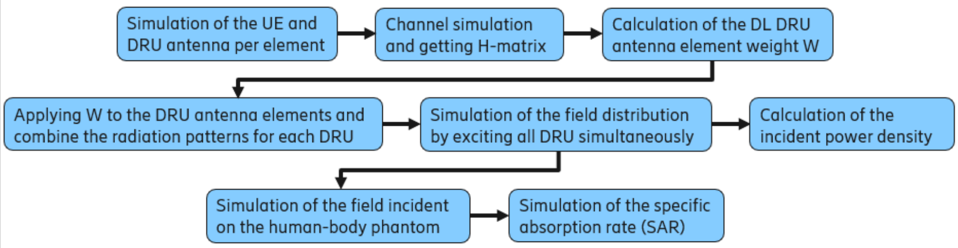

Figure 7-10: Workflow for the assessment of the EMF exposure in D-MIMO scenario by using the proposed simulation scheme.

Description: This deliverable presents a novel simulation workflow dedicated to EMF assessment of a D-MIMO deployment in an indoor industrial scenario at 3.5 GHz. The schematic diagram is given in Figure 7-9. In the ICNIRP guidelines, two types of EMF exposure limits are provided. The so-called basic restrictions are defined in terms of the power deposited in the human body. At 3.5 GHz, the relevant basic restriction quantity is the specific absorption rate (SAR) with limit values defined for SAR averaged over the whole body and over a sample cube volume of 10 g tissue. However, the basic restrictions are usually difficult to assess. Therefore, the ICNRIP guidelines provide another type of EMF exposure limit, so-called reference levels, which are to be assessed in free space. The reference levels are derived from basic restrictions under worst-case conditions. At 3.5 GHz, the relevant reference level metric is incident power density. This deliverable presents the simulation workflow for assessing both SAR and incident power density.

A scheme of the simulation workflow is presented in Figure 7-10. It starts with simulating the UE and distributed radio unit (DRU) antennas per element. For each antenna element, the equivalent far-field source is stored. In the next step, all far-field sources will be placed in the considered indoor industrial environment and for the sake of evaluating the basic restriction, a human-body phantom will be placed close to the UE antenna. By using the far-field sources, channel simulation will be performed. Thus, the channel matrix, with H_{ij}, being the channel transmission coefficient from the i^{th} element of DRU antenna to the j^{th} UE antenna element, will be obtained. By using the H-matrix the weights for the DL DRU elements, for the selected precoding scheme, will be evaluated. The weights will be applied to the DRU antenna elements. The radiation patterns of all antenna elements for each DRU will be combined into one far-field source. All thus obtained far-field sources will be placed in the considered indoor environment, keeping the same locations as in the channel simulation, and they will be excited simultaneously. In this way, the field distribution will be simulated which will later be used for evaluating the incident power density in the environment. The field incident on the human-body phantom will also be simulated and used for assessment of the SAR, which arise only in lossy tissue.

The simulation scheme will allow different number/density of the DRUs to be used. Moreover, using the proposed simulation scheme, the statistical SAR and incident power density distribution in the selected indoor industrial model is to be computed when the receiving antenna of the UEs and the human-body phantom are placed in different locations in the simulation environment. The proposed simulation scheme will also be developed so that the EMF exposure evaluation with different antenna precoding schemes, e.g., zero-forcing, and with one or multiple UEs. The proposed simulation scheme will also be applied to a massive MIMO antenna deployment, Thus, a comparison between D-MIMO and massive MIMO technology in terms of EMF exposure levels will be performed.

KPIs/KVIs: EMF compliance with international and EU recommended limits

Benchmark: 1). International and EU recommended EMF limits. 2). Statistical EMF exposure levels from a reference massive MIMO antenna under the same conditions

7.2 Massive MIMO schemes and architectures

This section presents massive MIMO enablers including hybrid analogue-digital architecture, and fully digital architecture with low resolution converters.

7.2.1 Hybrid analogue-digital architectures

7.2.1.1 sub-THz D-MIMO assisted by a sub-6 GHz macro network

Practical beamforming systems at sub-THz will rely on analogue beam steering with high-gain, narrow-beamwidth beams. A large number of such beams is needed to cover an angular scope of a network infrastructure node (e.g., on the order of 100 beams). As the link quality at sub-THz frequencies is sensitive to blockage, links with a satisfying link budget and outage probability will in most cases be LoS links. It is therefore of importance to ensure a high probability of LoS in practical sub-THz deployments. One technique for increasing the LoS probability is a dense deployment of sub-THz nodes (access points, APs) connected to a CPU, forming a D-MIMO network. The fundamental challenge in the sub-THz D-MIMO network will be the beam search at the network side, due to a large number of beams to be searched (e.g., on the order of 1000 or 10 000).

Description: the proposed solution to the above problem is using the uplink channel characteristics from the target user device to a macro coverage node operating at a frequency substantially lower than sub-THz (concretely, below 6 GHz) to infer the best low-order candidate list for a beam search in the downlink of the sub-THz D-MIMO network towards the target UE. The proposed concept is illustrated in Figure 7-11: user sends an uplink pilot to the sub-6 GHz base station (step 1), beam candidates for D-MIMO are inferred from the uplink estimate and sent to associated access points (step 2), access points perform a focused downlink beam search (step 3). A similar setup has been analysed in [AA20] for a single mmWave node; here, the concept is extended to multiple mmWave/sub-THz nodes.

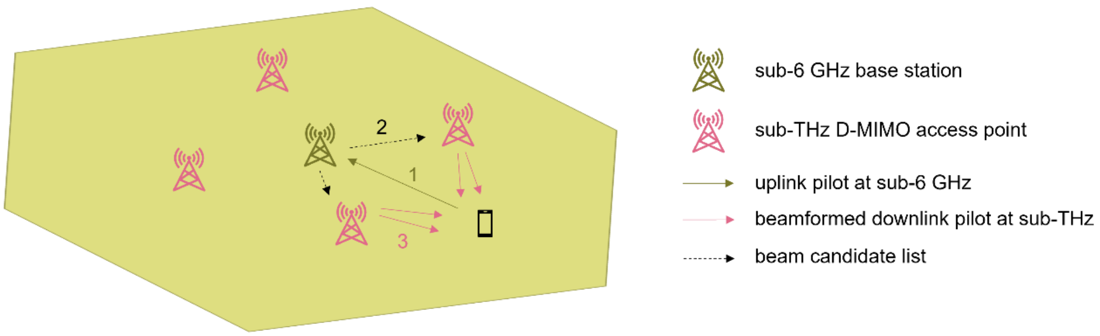

Figure 7-11: sub-6 GHz assisted beam search in sub-THz D-MIMO

KPIs/KVIs: main KPI is the time-frequency resources needed for control signalling needed for beam measurement and reporting in the downlink.

Benchmark: main benchmark for comparison is the sequential or hierarchical beam search based on downlink reference signals.

Assumptions: sub-6 GHz macro coverage node and the sub-THz D-MIMO network are assumed time synchronized and interfaced to a common logical control node. The user device is assumed to support operation on both sub-6 GHz and sub-THz frequencies, either simultaneously or with possibility of fast switching between the two operation modes.

7.2.2 Fully digital architectures with low-resolution ADCs/DACs

Compensating for the strong pathloss and penetration loss in the sub-THz band calls for massive MIMO arrays at the transmitter and/or at the receiver [RAB+20]. Fully digital architectures (with one RF chain per antenna) guarantee flexible wideband beamforming and large-scale spatial multiplexing as opposed to their hybrid analogue-digital counterparts (with fewer RF chains than antennas). However, the power consumption of each ADC/DAC scales linearly with the sampling rate and exponentially with the number of quantization bits

[ATD21]. Fully digital architectures with low-resolution ADCs/DACs (even down to 1-bit) can outperform hybrid analogue-digital architectures in terms of spectral and energy efficiency. 1-bit ADCs/DACs are particularly appealing as they can greatly simplify the RF architecture. Furthermore, the performance loss due to the 1-bit quantization can be compensated for by increasing the number of antennas and RF chains, which have very low cost and complexity due to the presence of 1-bit ADCs/DACs [AT22, AUA+23, RAT23].

Description: Hexa-X-II will provide an analytical framework to identify the scenarios where fully digital architectures outperform hybrid analogue-digital architectures in terms of spectral and energy efficiency. Furthermore, efficient algorithms for symbol-level precoding with 1-bit DACs will be developed considering hardware non-linearities and other undesired effects such as out-of-band emissions. Low-complexity and low-signalling schemes for initial access will be designed to enable the implementation of low-resolution ADCs/DACs in practice.

Use cases: Fully digital architectures with low-resolution and 1-bit ADCs/DACs can be implemented wherever flexible wideband beamforming and large-scale spatial multiplexing are needed, e.g., in indoor/outdoor scenarios and for wireless backhaul. Thanks to their reduced complexity and power consumption, they can be implemented also at the UEs. Use cases include fully merged cyber-physical worlds, digital twins for manufacturing, immersive smart cities, and e-health for all.

KPIs/KVIs: Higher spectral and energy efficiency, lower hardware complexity and cost, lower computational complexity, improved beamforming flexibility.

Benchmark: Hybrid analogue-digital architectures operating at the same frequency.

Assumptions: The antenna array must be sufficiently large to compensate for the coarse quantisation introduced by each ADC/DAC.

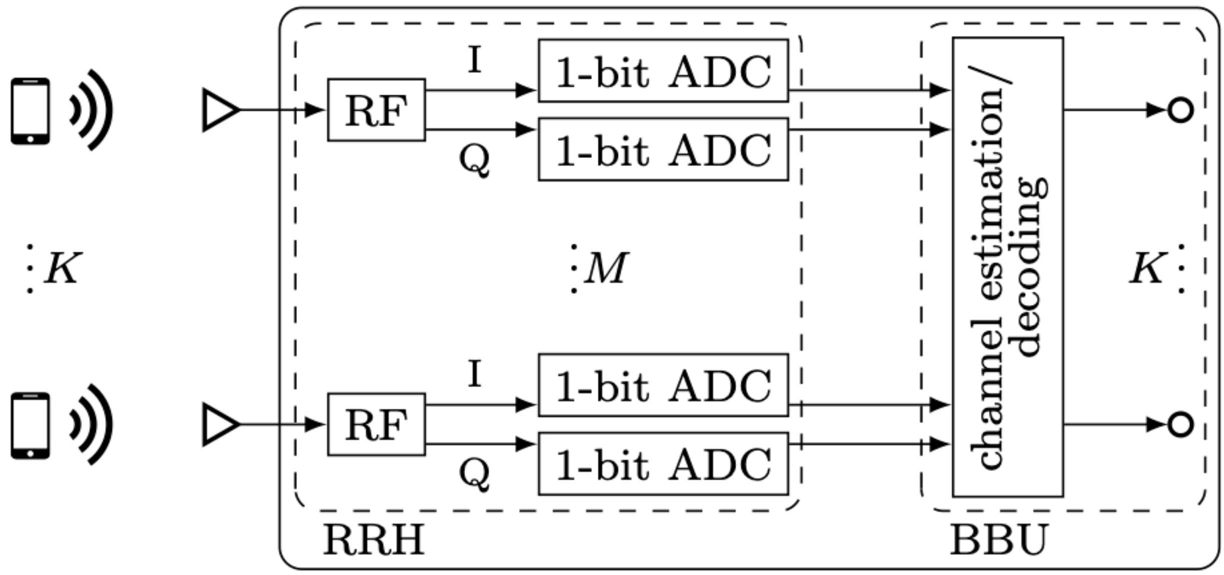

Figure 7-12: Fully digital uplink MIMO architecture with 1-bit ADCs.

7.3 RIS-assisted transmission

RIS [MDD+19] are a novel type of node in the network that influences the radio propagation between a transmitter node and a receiver node, in a passive way, i.e. without generating additional waves. Several types of influences (or operating modes) of RISs have been identified and listed by the European Technology Standardisation Institute (ETSI) Industry Specification Group (ISG) on RIS, and reported in [ETSI 001], [ETSI 002] and [ETSI 003]. The following types of influences have been listed: reflection, refraction, absorption, backscattering of impinging waves. RIS devices with one or several of these operating modes are expected to boost the network performance, very locally, close to them [RISE-6G D2.3] and [RISE-6G D2.4] and with some control by the network and or the UE [RISE-6G D6.5]. A large number of schemes of joint optimisation of transmitter beamformers, receiver schemes and RIS tuning, have been proposed. In [RISE-6G D4.2] a large number of schemes are proposed to optimise the network connectivity in terms of Spectral Efficiency, latency and robustness, in [RISE-6G D5.2] many schemes are proposed to boost the localisation accuracy based on wireless networks and even enable localisation with less than three network nodes (therefore without conventional triangulation). Finally, in [RISE-6G D6.2], many schemes are proposed that improve the ratio of the achieved spectral efficiency at the target UE over the EMF exposure of non-intended users, the secret spectral efficiency and the energy-efficiency. Regarding the maturity of the technology, recently, prototypes of RIS devices, for various frequencies (sub-6 GHz, mmWave and sub-THz), and various types of influences (reflection and refraction), all developed in Europe have been reported in [RISE-6G D3.4].

Finally, the spatial area of influence (AroI) of a RIS (i.e. the area in space where it significantly influences the coverage of a service, or a given performance metric), and the bandwidth of influence (BoI) (i.e. the range of frequency of impinging waves that will be affected by the RUS) have been recently introduced in ETSI ISG RIS [ETSI 003] and characterized numerically [APK+23].

7.3.1 RIS control procedure, interface, integration

Following three aspects relevant for control, connect and integrate of RIS in a communication-networks will be discussed:

- Signal level analysis,
- RIS controlled by UE,
- RIS controlled by others (e.g., factory automation system).

The case where the RIS is controlled by the radio communication network is very efficient and a first approach is shown in Section 7.3.1.1. A signal level analysis in a simplified propagation scenario is derived in this section. The effect of RIS on the signal received by the user is evaluated, considering both passive and active RIS.

7.3.1.1 Signal level analysis for RIS in a simplified scenario

RIS is expected to bring significant coverage and capacity gains in future 6G wireless networks. The derivation of a signal model for passive RIS highlights the “double fading” effect, for which the equivalent pathloss of the transmitter-RIS-receiver link is the product, instead of the summation, of the path losses of the transmitter-RIS link and RIS-receiver link [OBL+19]. The pathloss of the reflected link is then usually much larger than that of the direct link, and the expected gains from the introduction of RIS may reduce when the direct link is not completely blocked. To overcome this physical limit, the concept of active RIS that can also amplify the reflected signal has been recently proposed [ZDC+23].

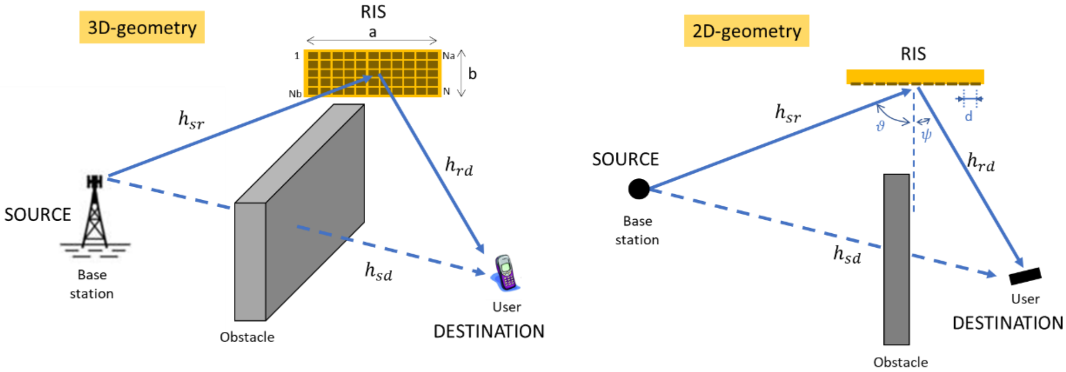

Figure 7-13: RIS application in a simplified propagation scenario

Description: A signal model for calculation of the SNR at the user receiver is derived, considering both passive and active RIS. The effect of RIS on the signal received by the user is then determined in a simplified propagation scenario, as the one depicted in Figure 7-13. The effect of the direct link, with different levels of blockage, is also analysed to highlight the potential gains from the introduction of RIS in the system.

Use cases: Higher penetration and blockage losses are a major drawback for mmWave and sub-THz frequency bands. By improving radio coverage, the proposed enabler is beneficial in use cases where radio propagation is hindered by the presence of obstacles such as in urban or industrial environments. The proposed enabler can then be beneficial in the "Immersive smart city", "Interacting and cooperative mobile robots" and "Small coverage, low-power micro-network in networks for production and manufacturing" use cases, where a small to very high number of users and devices must be served simultaneously in a challenging propagation environment.

KPIs/KVIs: Relevant KPI is the improved radio coverage achievable with RIS quantified by the calculated SNR at the user receiver. Relevant KVI for this enabler is Trustworthiness and in particular Reliability given the ability of RIS to introduce spatial diversity in the radio propagation environment.

Benchmark: Signal level analysis with RIS in a simplified propagation scenario. The performance in terms of SNR at the receiver is compared between a RIS assisted wireless system that employs either passive or active RIS and a baseline system without RIS.

Assumptions: Ideal RIS operation with perfect CSI knowledge is assumed. Effects related to the RIS implementation such as hardware impairments are not considered in the analysis.

7.3.1.2 Control procedures for personal RIS

To obtain a cost-efficient coverage extension and LoS blockage solution, control procedures will be designed to integrate RIS into radio networks. The main scenario of interest is indoor high-frequency local communication (mmWave or sub-THz). It is known that in this scenario RIS could be physically small, but it should be located close to either transmitter or receiver. Based on these assumptions, the focus of the planned research is on personal RIS, which could be considered as a personal device or as a part of user equipment.

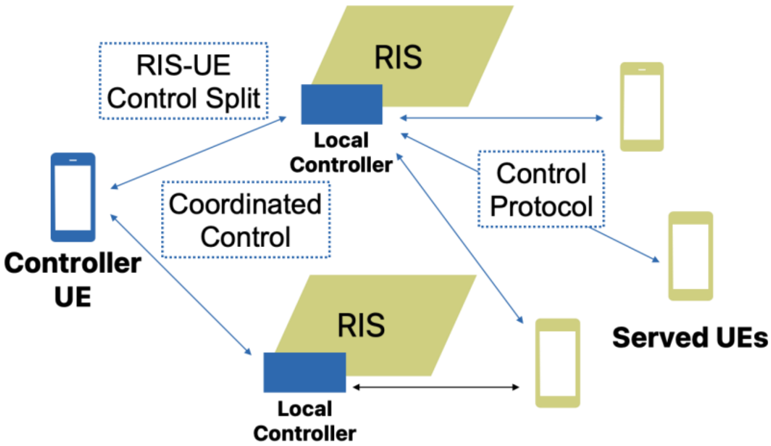

Figure 7-14: Schematic diagram of a personal RIS control solution.

Description: The focus is on design control procedures for non-radiative RIS with wireless control. Given the considered target use cases, the wireless control of RIS can be implemented independently of the radio-access network, e. g., control functionality can be split between UE and RIS itself. The control procedures include:

1. RIS discovery and connection establishment procedures
2. Control protocol for personal RIS
3. Integration of RIS control in high-frequency beam management procedures

Use cases: Short-range high-frequency mobile communication: indoor communication, body area communication, local D2D communication. LoS blockage is considered to be the key challenge.

KPIs/KVIs: The key KPI is coverage in LoS blockage scenario. Performance metrics of a LoS vs a blocked LoS and RIS scenario will be assessed against each other.

Benchmark: A high-frequency system without RIS is compared against the enhanced system including RIS.

Assumptions: It is assumed that RIS is a personal device of a limited size, equipped with a local controller unit. Local controller unit has capability to communicate with UE, AP or both. Communication can be performed via separate control RAT (WIFI, BT, …) or via data RAT (6G). Moreover, UE is capable to implement RIS control functionality.

7.3.1.3 Control procedures for externally controlled RIS in industrial environments

In industrial environments, there is a trend to track and optimize the positions and movements of workers or objects to improve safety and productivity. It is then beneficial to deterministically control RIS to improve coverage and link-performance based on data that is available in the factory automation system. For improving radio coverage with RIS in industrial environments the main interest is indoor communication in the FR1 and FR2 frequency bands. RIS will be placed at locations where coverage of critical areas or areas with high expected radio traffic can be improved. Based on these assumptions, RIS is considered as device that is controlled by the factory automation system.

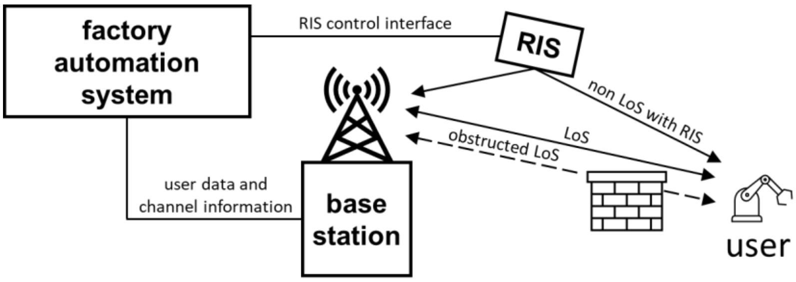

Figure 7-15 Schematic diagram of an industrial RIS control solution

Description: The focus is on control interfaces for RIS mounted at fixed locations in industrial environments. Given the considered target use cases, the control of RIS can be implemented by the factory automation system. Control efficiency can be improved by access to low-level channel information (e.g., RSSI). Procedures will be explored that are based on simulations. The control procedures include:

1. observation of communication quality and location of mobile devices,
2. beam management procedures that improve coverage, and
3. control of industrial RIS in the FR2 frequency band.

Use cases: The works considers short-range mobile communication in the FR2 frequency band for indoor communication in industrial environments. LoS blockage is considered to be the key challenge.

KPIs/KVIs: The most important KPI is coverage in blocked-LoS scenarios. Performance metrics of LoS, blocked-LoS, and blocked-LoS-with-RIS scenarios will be assessed and compared against each other.

Benchmark: The performance of a system enhanced by RIS will be compared with the baseline performance of a system without RIS.

Assumptions: It is assumed that RIS are devices equipped with a controller unit that controls the incoming/outgoing beams of the RIS. This controller has an interface to the factory automation system. A control protocol is used to control the beam-steering of the RIS. The parameters used for the RIS are based on practically feasible realizations and relay gain is the most important parameter.

7.3.2 D-MIMO assisted with RIS

RIS has emerged as a candidate technology for enabling the next-generation wireless networks, 6G [PRW+21]. By carefully modifying the wireless propagation environment, RISs can enhance the network coverage, circumvent signal blockage, increase the channel rank, reduce interference, enhance security, and more [DZD+20], [ESC+21], [TSS23]. Although, owing to the above advantages, the literature has abundantly studied the performance of RISs, most such studies concentrate on link-level, single-BS setups, and the characterization of multi-AP RIS-aided systems, such as in D-MIMO deployments, remains incomplete [LZ21]. One key aspect is investigating the performance of RISs deployed in a given area to meet prescribed KPIs.

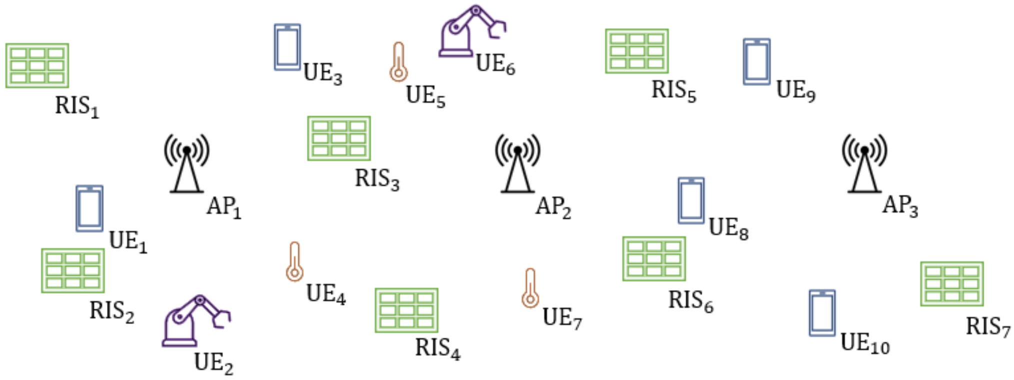

Figure 7-16: Multi-AP deployment with RISs serving various UEs.

Description: This work explores RIS-aided multi-AP systems attaining certain prescribed KPIs, while considering the energy consumption in the system. Both outdoor and indoor deployments are important. In outdoor deployments, boosting signal quality and reducing D-MIMO inter-cluster and inter-operator interference may be beneficial for several of the Hexa-X-II use cases, such as "e-health for all" and "energy-optimizing services" [GPS22]. In indoor environments, such as factory halls, RIS may also be beneficial for, e.g., cooperative robot (cobot) use cases. The performed analysis is based on system-level simulations of D-MIMO scenarios with multi-UE, multi-AP, multi-RIS setups, as exemplified by Figure 7-16, using realistic propagation channel models [38.901]. Each RIS may be configured into an absorptive, active, or passive operation mode. The combination of RISs with different operation modes enhances the controllability of the propagation environment. Manipulating the proportion of absorptive, active, and passive RISs in the system allows smooth adaptation to different requirements and environments. For example, in high-interference environments, the system could favour absorptive RISs to reduce interference, whereas in energy-constrained areas, the system might benefit from passive RISs. Moreover, in coverage-constrained areas, active RISs can help the system. Planning the RIS placement for such heterogeneity will also further enhance the performance. The analyse will be conducted for selected Hexa-X-II use cases. The aim is to provide some guidelines as to how to deploy, select and control RISs in practical multi-UE, multi-AP, multi-RIS deployments.

Use cases: This enabler relates to Hexa-X-II use cases "e-health for all" [Hexa-X, D1.2, 4.2.2.1], "interacting and cooperative mobile robots" [Hexa-X, D1.2, 4.2.5.3], and "energy-optimizing services" [Hexa-X, D1.2, 4.2.7.5]. In outdoor environments, RISs can work as coverage extenders, while indoors, they can provide redundant paths between the network and the UEs, thus enhancing dependability. Energy-optimized services may select RIS-enabled paths to reduce end-to-end energy consumption.

KPIs/KVIs: This enabler is related to KPIs, KVIs enabling the UN sustainable development goal (SDG) 3.8, UN SDG 3.8 ("e-health for all"), and UN SDG 9 ("interacting and cooperative mobile robots") use cases. Moreover, RISs can be used to improve the availability and reliability of services. Other relevant KPIs that may be used are the spectral efficiency, the outage probability, and the energy consumption, including the energy required by the UEs for communication.

Benchmark: The performance of RIS-aided multi-BS setups can be compared against that of traditional systems without RISs. Also, the performance against various types of RISs including active, passive, and absorptive can be considered for further insights.

Assumptions: This work assumes that the RISs can be controlled by the network, at least partially, and that required channel state information is available.

7.3.3 Channel estimation for RIS

With the rise of autonomous driving and improvements in safety and comfort applications, vehicular communication has become increasingly important. However, wireless communication between vehicles and other devices is often hindered by the unpredictable nature of wireless propagation. To address this issue, RIS has been introduced. These surfaces allow for software-controlled reflections to help manage the wireless propagation environment [WZ20]. Despite their potential benefits, there are several challenges that need to be addressed before RISs can be effectively used in vehicular networks. One major challenge is channel estimation, which requires pilot signals received at the BS due to the passive nature of the RIS. This requires significant resources as RISs consist of numerous reflecting elements, and the constant changes in wireless channels caused by mobility necessitate frequent channel estimation, which results in excessive overhead for RIS aided systems.

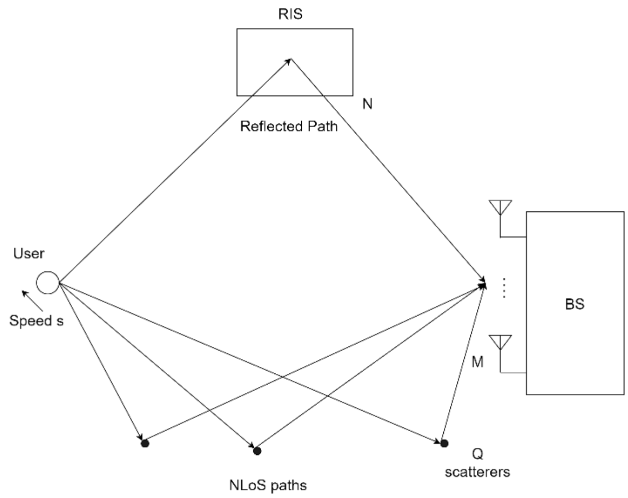

Figure 7-17 Illustration of the channel model for an RIS assisted vehicular user.

Description: In this work an ML based channel estimation scheme for RIS aided systems while considering mobility is proposed. The uplink channel estimation of a mmWave vehicular network is considered, which consists of a BS with M antennas and a single antenna vehicular user, assisted by an RIS with N reflecting elements. Reflecting elements are arranged in G uniform groups (i.e., reflecting elements in a group share the same phase shifts and are assumed to have the same channel coefficient as well) to reduce the pilot overhead [DMR+21]. As illustrated in Figure 7-17, the channel consists of a direct link which is NLoS, and a reflected link through RIS which is assumed to be consisting of LoS components. The sparsity of the mmWave scattering channel is used to represent the system in a compact notation which consists of the angle of arrivals (AoA), complex path gains and Doppler shifts for different paths as parameters [DMR+22].

Use cases: This can be applied in "*Interacting and cooperative mobile robots"* use case in Section 2.3.1 to improve the communication performances with improved channel estimation accuracy.

KPIs/KVIs: Relevant KPI is to improve channel estimation accuracy quantified by NMSE, for both direct and RIS channels.

Benchmark: An ML based solution will be compared against an optimization solution and a genie aided solution with known AoAs.

Assumptions: Consider an ideal RIS (i.e., without any hardware impairments), and disregard any synchronization issues that may arise.

7.3.4 Learn RIS-RM

RIS is an emerging technology for configuring favourable wireless communication environments. The recent research direction of reflecting modulation (RM) for RIS-based communications is a promising information transfer mechanism, which does not require any additional radio frequency chains [LCW+22], [GLZ+20]. RM allows both the reflecting patterns and transmit signals to carry information, enabling the transmitter and RIS to deliver information jointly or independently.

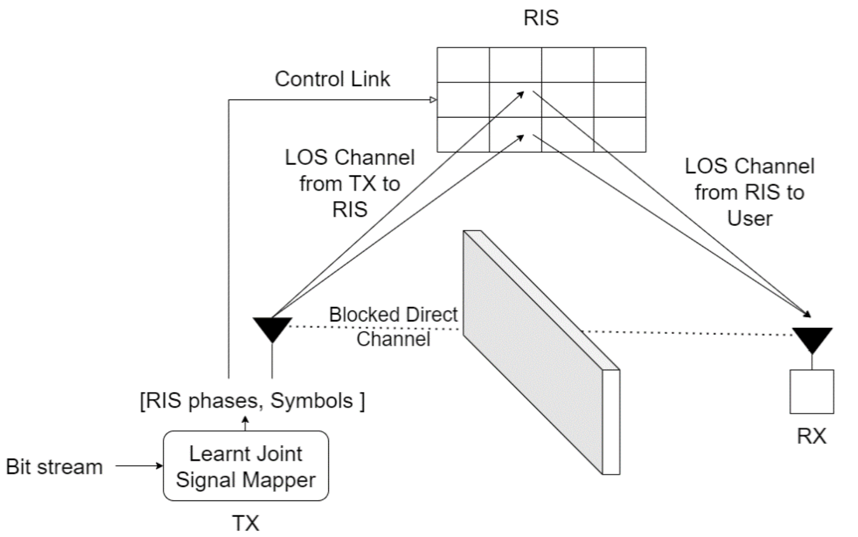

Figure 7-18 Illustration of a RIS-based RM communication system

Description: The signalling set for RM consists of the constellation points and the reflection patterns. They can be separately or jointly mapped to modulate the bit stream. It has been shown that separately mapping the signalling set is sub-optimal [KSR+21]. An optimization-based signal mapping and reflecting pattern design for jointly mapped and separately mapped RM to minimize the system BER with a given transmit signal candidate set and a reflecting pattern candidate set has been proposed in [GLZ+20]. However, it becomes a difficult task to design the signal set with increasing number of RIS elements. Therefore, in this work, an algorithm is proposed to learn the joint signal mapper based on an ML approach which provides optimal signal set (constellation and the reflecting pattern).

Use cases: With higher frequencies predominantly relying on LoS links, RIS enables a way to extend the coverage and ensure LoS-like link to the user. With reflecting modulation enabled, more information can be reliably conveyed to the user, and the solution to the problem of having a larger number of RIS elements is expected to be addressed with this work. This could be featured in the use case, "Immersive smart city" (Section 4.2.3.2 in Hexa-X D1.2), which the improved link will ensure coverage in an urban scenario where blockage is unavoidable.

KPIs/KVIs: Throughput, BER and other relevant KPIs related to RIS assisted transmissions.

Benchmark: The solution will be compared to RIS based system without reflection modulation to quantify the gain provided by the reflection modulation scheme.

Assumptions: Ideal RIS with perfect synchronization and the reflection patterns signalled via a feedback link to the RIS from the TX.

8 Flexible spectrum access solutions

This chapter covers spectrum sharing and coexistence aspects as well as low-latency spectrum access methods including three enablers related to spectrum sharing and coexistence with different services and previous generations, considering NTN and interference management methods, and two enablers on low-latency spectrum access methods for local area and low-power UE connectivity, combined with risk-based spectrum access. On NTN, this chapter focuses on satellites.

Those technical enablers will contribute to sustainability, inclusion, and trustworthiness values according to Section 2.2 as follows:

- Sustainability: The minimization of energy consumption is a key guiding principle when selecting a network or network type, NTN or TN. Low-latency access to spectrum reduces random access energy consumption. Furthermore, reusing base station sites when upgrading from one cellular generation to the next, e.g., via dynamic MRSS, will improve deployment efficiency and economic sustainability.
- Inclusion: NTN enables access in earth locations where mobile broadband is not available otherwise. Low-latency spectrum access targets a fair access to spectrum for all users.
- Trustworthiness: A diversity of networks where one can select the most trustworthy or available network leads to a higher service dependability. Accordingly, a reliable and low-latency access to spectrum contributes to good user experience.

Performance indicators (Section 2.1) that will be improved include, in the case of spectrum sharing and coexistence, capacity of both NTN and TN, base station separation distance, and energy consumption; and C-plane latency, access capacity, and energy consumption in the case of low-latency spectrum access.

Related use cases with specific requirements to spectrum usage include [HEX22-D13]

- Earth monitoring: wide coverage, use of NTN, sensing, energy-harvesting devices
- Immersive smart city: massive scale, low-power devices, time-variable load
- Merged reality game and work: large bandwidth, low-latency random access
- Interacting and cooperative mobile robots: sensing, low-latency random access
- Micro-network for manufacturing: local spectrum usage in small areas
- Flexible device type change: dynamic spectrum on a device basis

8.1 Spectrum sharing and coexistence

New use cases that will emerge with 6G, together with the expected exponential growth in mobile broadband traffic, will translate in a need for additional spectrum to the one available nowadays. Just considering a set of 6G use cases would require around 3 GHz of wide-area spectrum [Eri23], which is far from the one that will be made available in optimal scenarios. It is calculated that there will be a shortfall of 1.5-2.2 GHz of spectrum by 2030, depending on the market [Eri23]. Therefore, there is a reasonable chance that mobile services will need to coexist or share spectrum with other incumbents in new centimetric bands, i.e., 7-15 GHz frequency range.

8.1.1 Assumptions and models to determine sharing possibilities

A way forward in the improvement of sharing possibilities between mobile networks (i.e., International Mobile Telecommunications – IMT) and other radio services is to establish more realistic assumptions and scenarios. This is expected to result in better coexistence conditions between IMT and other radio services, e.g., shorter separation distances and fewer restrictions on IMT base station total radiated power (TRP) or conducted power.

Description: The deployment of IMT networks needs to consider certain protection criteria to protect other radio services. To do so, protection conditions are established, e.g., spatial separation distances between radio stations, transmit power limits, etc. In certain cases, these protection conditions are stringent and impose harsh restrictions on the deployment of IMT networks limiting its performance and coverage. To determine these conditions, typical assumptions on the system and deployment related parameters must be done covering from antennas radiation patterns to network topologies. Usually, these assumptions are based on simplified models that tend to overprotect radio receivers and, therefore, impose unnecessary restrictions on IMT base stations. For example, in case of protecting fixed-satellite service earth stations (FSS ES), it is important to account for the following aspects: the FSS ES antenna efficiency is below 100%, the actual gain of the antenna sidelobes is below the typically assumed values in the gain mask provided in [ITU-S.465], the antenna noise temperature is dependent on the antenna elevation angle [ITU-S.733], among others. Also, for fixed service (FS) and FSS space stations receivers (e.g., for spot beams) similar assessments apply. Thus, to determine more accurate protection conditions, more realistic assumptions should be considered when available. For this purpose, if the real antenna parameters and radiation patterns are considered (see Figure 8-1), the protection conditions can be alleviated and lead to a more efficient deployment of IMT networks.

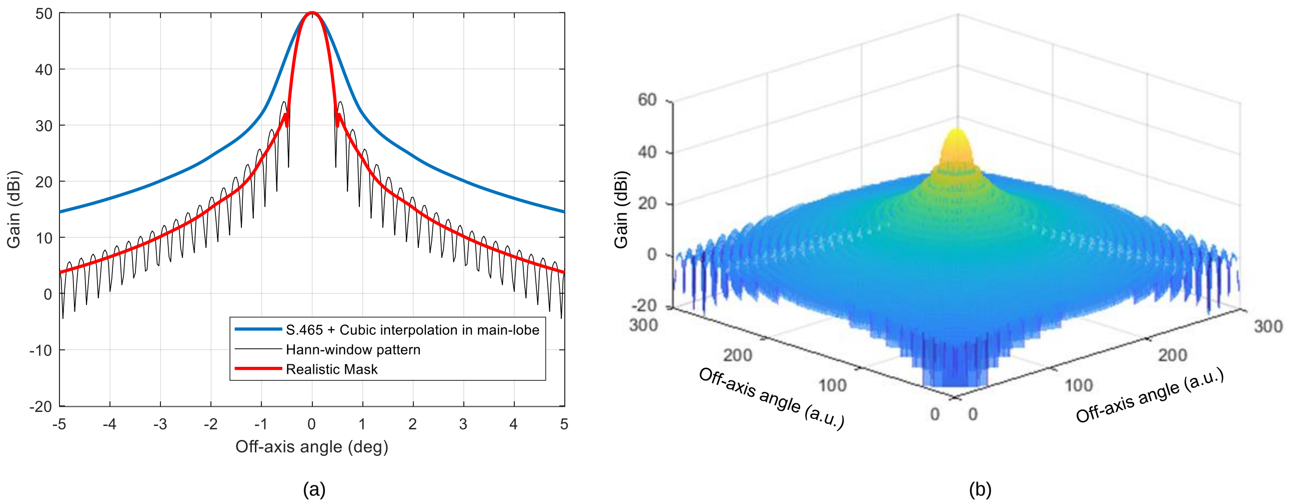

Figure 8-1 FSS earth station realistic antenna gain pattern. (a) Transversal cut comparison of ITU-R S.465 antenna model and a realistic Hann-window based model. (b) 3D Hann-window based model.

KPI: Separation distance between two different radio services that share spectrum or other protection conditions (e.g., TRP limits) to prevent harmful interference to radio services receivers, e.g., FSS ES and FS stations.

Benchmark: International Telecommunications Union Radiocommunication Sector (ITU-R) Recommendations and Reports, e.g., ITU-R Report [ITU-S.2368].

Assumptions will be made on antenna configurations and radiation patterns (IMT and other services), beamforming, network topology, propagation models, and protection criteria of radio services receivers, e.g., FSS ES and FS stations.

8.1.2 TN-NTN spectrum coexistence and sharing frameworks

NTN will likely require more spectrum to effectively provide their services. Since TN and NTN serve users in different areas, this opens up the potential for effective spectrum sharing between the two. A distinctive characteristic of NTN cells, especially those associated with LEO satellites, is their mobility. This means that they may move over time, changing the dynamics of network configuration and connectivity. Another important aspect of this coexistence and spectrum sharing is the need to understand the interference patterns and risks between TN and NTN. This includes interference risks with other satellite devices as well.

The focus here is specifically on exploring the sharing possibilities between LEO satellite networks and terrestrial cellular 6G networks. This cross-network cooperation could lead to more efficient use of available spectrum and better overall connectivity for end users.

Different sharing solutions, including sensing and AI-based solutions are discussed in this section.

Description: The outcome of this task will be twofold: a comprehensive system architecture and the development of spectrum sharing criteria (e.g., limiting radiated power and other antenna design characteristics) and selection algorithms. The system architecture will provide a detailed overview of the structure and interaction of the elements involved. The sharing criteria and selection algorithms will provide a systematic approach to efficiently allocate and share the spectrum between different network entities.

An illustration of the two interfering networks is shown in Figure 8-2. In the context of the spectrum used by satellites, and the potential coexistence scenarios with other networks, it's important to identify three different types of connections, also known as links. The first type is the feeder links. These are essentially the connections between the gateway or earth stations and the satellites. They are responsible for transmitting user data across long distances, from the ground to the orbiting satellites (uplink) and vice versa (downlink). The second type is the service links. These links exist between the satellites themselves and the terminals on the ground. They are responsible for delivering user data from the end users' devices to the satellites (uplink) and vice versa (downlink). The third type of link is used for tracking, telemetry, and control data. Like the feeder links, these connections are also between the gateway or earth stations and the satellites. However, instead of user data, these links transmit operational data to monitor and control the satellites' functions. These three types of links are critical for the successful operation of satellite-based communication networks; understanding them is a vital part of this research task.

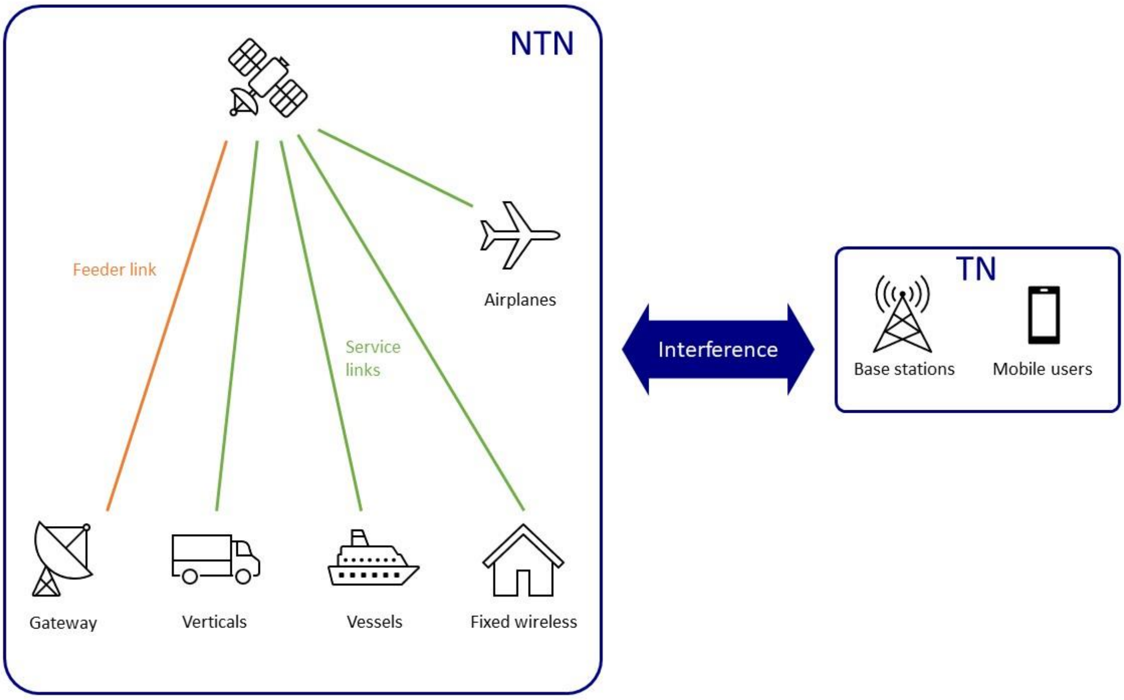

Figure 8-2 Illustration of the two blocks that might interfere. On the left, NTN system including feeder and service links. On the right, mobile network.

Spectrum sensing refers to the task of gaining awareness about the spectrum use in a particular geographical area, not to be confused with Joint Communication and Sensing. It can be employed to detect incumbent or peer transmitters, or alternatively, to collect longer-term data about the utilization rate of a certain frequency channel or band in a given area. This data can then serve as an input for spectrum databases.

Spectrum sensing is projected to be a vital feature of 6G networks, requiring the spectrum to be allocated accordingly. It can be utilized to optimize both resource and spectrum allocation, improving the overall efficiency of the network. These networks will natively support AI and ML, leading to the potential of achieving global connectivity for everyone and everything. This applies to a variety of use cases, such as earth monitoring, among others.

AI, particularly ML, can be instrumental in handling the vast and complex data associated with spectrum sharing and interference calculations. However, the sensitivity of spectrum sensing needs to be carefully understood and modelled to prevent failures, as seen in earlier cognitive radio attempts with spectrum sensors.

The system architecture will include sensing and ML servers, with ML-based algorithms playing a crucial role. Spectrum sensing will be performed by the TN to protect both the TN and the NTN from harmful inter-network interference. A database for dynamic spectrum sharing (DSS) will be set up with AI support to optimize the process. It is to be noted though that many TN services rely on predictable spectrum availability/access and high QoS, meaning that such a database would need to guarantee spectrum resource availability when needed for this concept to work. Alternatively, this concept could be applied to less critical use cases and services where delays and best effort performance are acceptable.

KPI, KVI: KPIs will include communications KPIs such as throughput, capacity, and latency, as well as sensing KPIs like resolution, accuracy, and detection/false-alarm rate. Additionally, the capacity in the incumbent services is also of significant interest, ideally maintaining the same level as when not sharing the spectrum**.** Energy efficiency will also be a significant factor. The KVIs addressed will be sustainability (more efficient use of the energy resources), inclusion (connection to remote areas), and trustworthiness (network should be reliable).

Benchmarking will be conducted against the same network operating without spectrum sharing, as well as against networks with static spectrum allocation, and networks without ML and sensing support. These comparisons will provide valuable insights into the efficiency and effectiveness of the proposed spectrum sharing mechanisms and algorithms.

Assumptions that underpin this research include the use of LEO satellites. The research also assumes that these satellites will be used to provide coverage for remote and rural areas. These assumptions are vital as they define the context and the scope of the network architecture, sharing algorithms, and performance indicators being investigated. Furthermore, assumptions underpinning this research include specifics about antenna patterns, network topology, beam forming, and transmission power, including spectral masks. These factors will shape the system architecture and performance of the 6G network under study.

8.1.3 Multi-RAT spectrum sharing

The introduction of RAT generations prior to 5G was driven in part by the availability of new spectrum and static re-farming of existing spectrum resources towards the new generation. Spectrum scarcity and device penetration have increased significantly since those days. Due to favourable propagation conditions, FR1 is the preferred spectrum band for cellular service providers (CSP). However, this band has limited available spectrum and is often highly loaded, and, therefore, achieving high spectral efficiency becomes critical in this scenario. Bearing in mind that little to no new sub-6 GHz spectrum is expected to become available in the key 6G markets by 2030, it becomes evident that the ability to leverage existing 5G spectrum will play a pivotal role in the successful and cost-efficient migration to a new RAT [Nok23]. Figure 8-3 illustrates the existing 5G bands, expected new bands for 6G and indicates where solutions for a smooth spectrum migration are mostly needed.

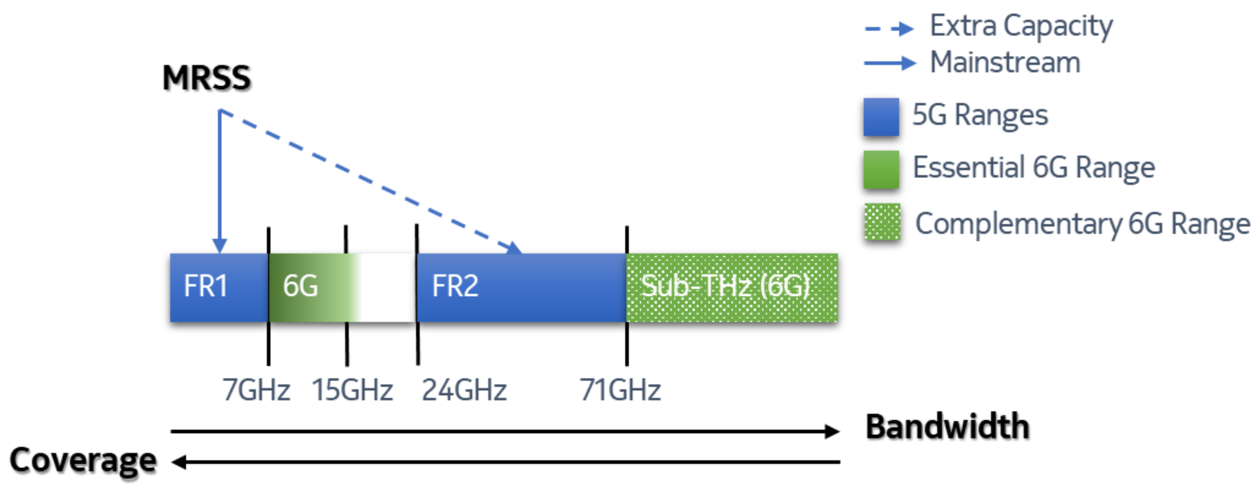

Figure 8-3 Existing 5G bands and expected new 6G bands.

Description: To address these challenges, the 5G-6G coexistence topic will be investigated and a structured solution to enable a smooth migration will be proposed. The starting point is a thorough analysis of the framework standardized by 3GPP to enable DSS between LTE and 5G NR. Practical implementation challenges will also be considered. This initial step aims to uncover both the strengths and weaknesses of the original concept, providing fresh insights for enhancements.

Currently, the 6G physical layer design remains unknown. However, the flexible and lean-carrier design of 5G NR is well known, and it can be leveraged to minimize unnecessary overheads that erode the overall capacity of the shared spectrum. In addition, the pros and cons of different 6G numerology, frame structure, waveform and spectrum aggregation mechanisms will be considered in terms of their impact on the spectrum sharing efficiency.

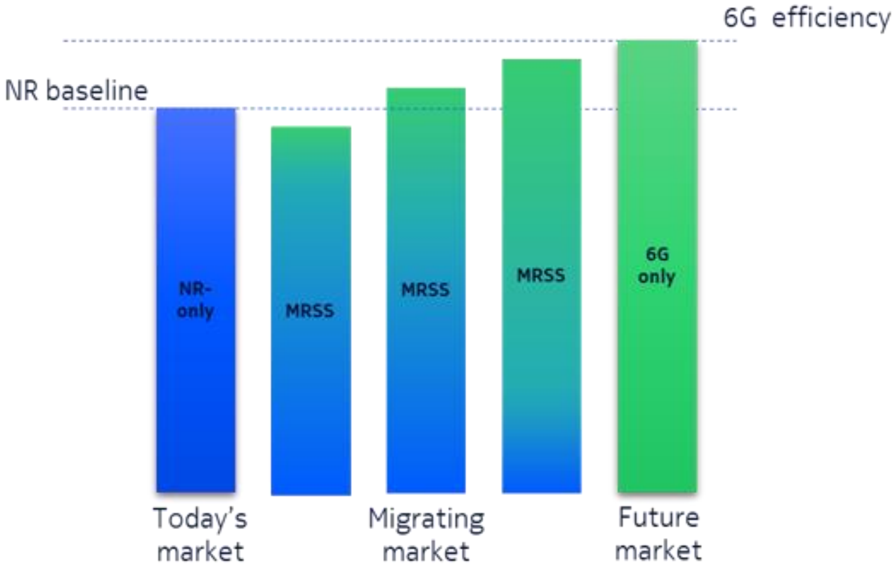

Figure 8-4 MRSS and the gradual transition from 5G to 6G.

Furthermore, the development of efficient scheduling algorithms will be crucial in optimizing resource allocation in response to real-time traffic variations, thus maximizing the overall energy and spectral efficiency of the shared radio. The overarching goal is illustrated in Figure 8-4. In other words, as the migration process progresses and uptake of 6G devices increases, the overall efficiency should approach that of 6G. In practice, MRSS is envisioned to be deployed in low frequency bands for coverage and then supplemented with MRSS deployments in mid bands for capacity, thus eliminating the need for new site acquisitions and paving the way for a smooth rollout of 6G cells during the early 2030s.

KPI, KVI: The analysis will consider traditional communication KPIs with special emphasis on those relevant for eMBB services, e.g., data rate experienced by user, area traffic capacity, latency, and energy efficiency. A design that facilitates minimization of energy consumption across multiple RATs ties into the sustainability KVI. At the same time, maximization of user data rates and cell capacity are important to ensure mobile connectivity is universalized thus contributing the inclusivity KVI. Finally, a smooth migration is important to guarantee service offered by the preceding generation is not disrupted by the introduction of 6G, hence an important technology component linked to the trustworthiness KVI.

Benchmarking will be conducted against a network without sharing as well as static re-farming arrangements, which will serve as baselines for evaluating the impact and effectiveness of the proposed framework for 5G and 6G coexistence.

Assumptions: Initial focus will be on outdoor cells and public cellular networks using dedicated spectrum in sub-6 GHz bands also known as FR1. The studies will put emphasis on an evolutionary 6G PHY design and assume that legacy devices do not support new features, i.e., MRSS is completely transparent to 5G UEs. Legacy LTE eNodeBs will not be considered.

8.2 Low-latency random access

Low-latency random access is required by many existing and emerging applications, e.g., XR gaming and collaborative robots. In the case of low-latency random access there are two different aspects that must be considered. First, the low-latency initial access to spectrum that can be extremely important for many control messages or rapid short-range communication bursts. Secondly, low latency (random access control) can be required during an already established communications session. These two perspectives are inter-related, but both are not always required.

Opportunities for enabling low-latency connectivity depend strongly on the used frequency bands and interference patterns. Particularly sub-THz and FR2 bands enable better spectrum reuse, opportunistic and risk based low-latency access due to limited coverage in these bands.

8.2.1 Sub-THz access methods

Spectrum access should be fast and reliable for a good user experience. High directivity of sub-THz communication allows to simplify certain procedures like collision avoidance and contention resolution, while making beam management even more important compared to FR 2. Relevant use cases include, e.g., merged reality game/work and interacting cooperative mobile robots [HEX22-D13].

Description: Sub-THz access schemes will be defined including timelines, multi-user handling, and conflict resolution. Focus will be on UE and base station interworking, initial data transfer, and beam pairing. Existing mechanisms, like for FR2 in 5G NR systems, IEEE 802.11ad/ay (WiGig), or IEEE 802.15.3d/e (300 GHz) will be analysed to identify reuse opportunities [JPY15, NCF+14].

The relevant use cases will be further broken down to allow validation of access schemes in terms of data rate or latency. Additional scenarios might need to be defined as baseline to enable further evaluation of access latency and capacity, see, e.g., Figure 8-5.

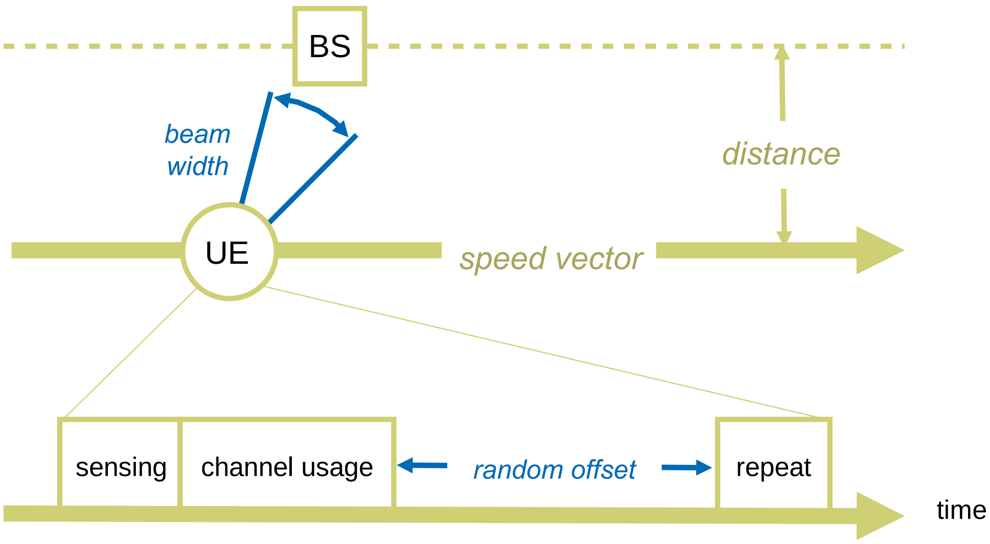

Figure 8-5 Exemplary scenario for low-latency sub-THz random-access.

KPI, KVI: Impacted KPI include access latency, access capacity, and access energy consumption. Low latency spectrum access is expected to address sustainability (reduced random access energy consumption), inclusion (fair access to spectrum), and trustworthiness (improved user experience in terms of service availability).

Benchmark for evaluation is 5G NR access for FR1 and FR2.

Assumptions: Initial focus will be on indoor scenarios and devices with limited output power. The frequency range 140–300 GHz is considered with a contiguous bandwidth of at least 10 GHz; accordingly, low-complexity waveforms like single-carrier systems with low-order modulation schemes and, to compensate for the high pathloss in this frequency range, steerable antenna arrays are assumed. A further assumption in this study is that certain bands in the sub-THz frequency range can be used without license.

8.2.2 Risk-informed random access

Probabilistic approach to spectrum sharing goes beyond considering only the total avoidance of interference but considers also risks involved in causing some extra interference. It also considers the risk level associated with different interference patterns and how much harm they could cause. The risk-informed random access can be seen as a new paradigm that borrows ideas from random medium access, while still considering coordinated spectrum access as the mainstream. Relevant initial use cases include, e.g., merged (augmented) reality game/work and interacting cooperative mobile robots [HEX22-D13].

Description: In certain scenarios, particularly in the case of D2D communications indoors, strict spectrum access rules and coordination requirements can be relaxed. The main underlying observation in the recent interest on risk aware regulation and spectrum access is that in RF-based communications the current *zero interference-based approach* is somewhat too strict and even unrealistic, compared to the possibly lost opportunities. A novel approach is to assess the potential harm caused by short-term, local interference and use this information to inform risk-based random access for selected services. This concept draws inspiration from risk-informed regulation and operations widely used in other engineering domains [FCC03].

The risk based or modified random access allows better reuse of spatiotemporal opportunities in spectrum allocation. The method is closely linked to different coexistence and sharing schemes, e.g., dynamic shared access (DSA), licensed shared access (LSA), and cognitive radio (CR), but brings in the concept of risk evaluation. The method opens also possibility to consider receiver-based regulation.

The relevant use cases will further consider the different frequency band effects with assumption that risk based random access is easier to guarantee in FR2 and particularly for sub-THz bands.

KPI, KVI: Impacted KPI include extra interference level (and “risk”) compared to classical licensed, orthogonal spectrum sharing, and consideration of access latency, access capacity, and access energy consumption (i.e., “opportunities provided”). Low latency spectrum access will have effect to sustainability (reduced random access energy consumption), inclusion (fair and cost-efficient access to spectrum), and trustworthiness (improved user experience in terms of service availability).

Benchmark is against the fully licensed and centralised spectrum access. Particularly the sub-THz bands case will be benchmarked against FR1 and FR2 opportunities to employ risk based random access.

Assumptions: Initial focus will be on indoor cells and sporadic D2D outdoor usage. Assumptions made in this research include considerations related to transmission power, shielded (indoor) locations, antenna patterns, and the distinction between licensed and unlicensed spectrum. These assumptions provide a framework for studying the impact and feasibility of the probabilistic approach to spectrum sharing. No assumptions on the licensing regime of sub-THz band at this stage is made.

9 Joint communications and sensing

This chapter comprises work on JCAS architectures, waveforms and frame structures, resource allocation, as well as security and privacy considerations.

Before describing the technical contributions, a summary of the used terminology is provided:

- **Positioning** refers to the estimation of the position of a connected device. Positioning may rely on sensing information.
- **Localisation** extends positioning to also include the estimation of the position of a passive object / target (e.g., device-free localisation).
- **Sensing** comprises receiving a radio signal or a set of radio signals and processing these radio signals to extract information relevant for a service. The received radio signals in general depend on the geometric state of the transmitter, receiver, and the environment (e.g., radar sensing), though not all sensing services rely on this geometry (e.g., pollution monitoring).
- **JCAS** refers to wireless systems that combines communication and sensing functionalities to re-use hardware, save resources (vs. having 2 systems), and/or for a cross-functional benefit. Not restricted to a particular usage of pilots or data symbols. Here, "sensing functionalities" encompasses sensing, positioning, and localization aspects. It is worth nothing that while in the literature the terms ISAC (Integrated Sensing and Communications) and JCAS (Joint Communications and Sensing) have been used both with different and similar meanings, in Hexa-X-II, they are considered to be equivalent.

Some of the architectures and resource allocation methods involve sharing information between different nodes (e.g., between UEs, between BSs, or between BSs and UEs). In such cases, the exchange of data between nodes, the type and quantity of data that needs to be shared, and the corresponding demands in terms of capacity, allowable latency, and synchronization, needed to support this sharing are questions of interest among the listed contributions. In this deliverable, the assumption is that such data sharing is supported, and that sufficient capacity is available. In future deliverables, a more quantified view will be taken to address this question.

9.1 JCAS architectures

Five distinct architectural solutions are considered, spanning NTN-aided localisation, integrated communication and monostatic sensing, integrated monostatic and bistatic sensing, and multistatic sensing.

9.1.1 NTN-aided localisation

NTNs are expected to play a key role in the upcoming 6G era, providing global coverage and enabling high-speed connectivity for a multitude of devices and applications [GZ21]. 6G NTNs comprise geostationary earth orbiting (GEO) satellites and LEO satellites [Ema21]. This task will investigate methodologies to extend the use case of NTNs to encompass localisation and positioning of UEs in urban, sub-urban, and rural areas (see Figure 9-1). Additionally, the integration of NTNs with TNs and RIS will be investigated to further enhance the localisation performance in urban areas. Such integration is expected to enable applications that will benefit from low-latency, reliable, and uninterrupted positioning services, such as autonomous vehicles (AVs).

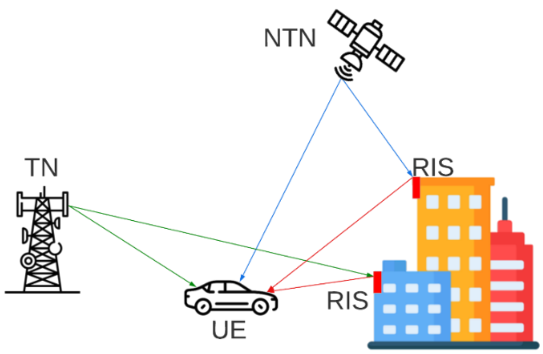

Figure 9-1 UE localisation through the integration between NTN, TN, and RIS.

Description: As the name suggests, GEO satellites are stationary with respect to a pre-set geographical area. Such satellites are found at high altitudes of 35,786 km with beam-sizes ranging from 200 to 3500 km [Ema21]. On the other hand, LEO satellites orbit the earth at a much lower altitude, i.e., 300 to 1500 km [Ema21]. LEO satellites thus have a smaller beam-size ranging from 100 to 1000 km [Ema21]. LEO satellites are usually of interest due to the shorter delay spread [KG21], lower sensitivity towards angular errors, and lower atmospheric effects (ionospheric and tropospheric); as opposed to GEO satellites [PFS+22]. At first, standalone (SA) LEO satellite positioning will be investigated and compared to SA TN positioning. Next, optimal integration between LEO, TN, and RIS will be explored. The integration can be done in a loosely coupled (LC), tightly coupled (TC), or in an ultra-tightly coupled (UTC) fashion, as shown in Figure 9-2. In LC integration, the fusion of the final positioning outputs of both networks will be studied. On the other hand, in TC integration, the individual positioning measurables from each network (i.e., range and angle measurements) will be integrated in a single filter. Finally, in UTC integration, each network's signals will be integrated on a fundamental level (i.e., raw measurements, such as IQ data), enabling enhanced positioning and mapping capabilities. The methods are expected to provide varying degrees of positioning accuracy and implementation complexity. Hence the need for exploration.

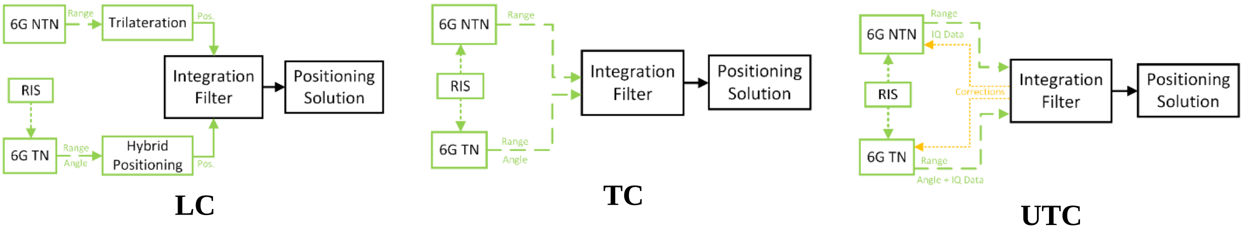

Figure 9-2 Modes of integration of NTN, TN, RIS.

Use cases: The integration between NTN, TN, and RIS is expected to enable applications that will benefit from low-latency, reliable, and uninterrupted positioning services, such as autonomous vehicles. Enabling AVs will support realizing use cases like "Immersive smart cities" and "E-health for all", where seamless high-precision positioning information is paramount. Accessing this information will significantly improve the efficiency and safety of ambulances, as well as public and goods transportation systems.

KPIs and KVIs: The main KPI of this task is the positioning accuracy, e.g., the root-mean square error (RMSE) in 2D or 3D or the error that can be attained 90% of space / time. Additional KPIs include availability (the percentage of time/space achieving a target positioning accuracy can be attained) and latency. The enabler relates to the KVIs by improving sustainability (e.g., accurate positioning will enable self-driving vehicles, which will decrease traffic congestion and will in turn reduce gas emissions), inclusion (by expanding positioning coverage to areas that have insufficient TNs), and trustworthiness (as redundancy formed by the integration of NTNs, TNs, and RIS will increase the robustness and trustworthiness of the positioning solution).

Benchmark: The main benchmark of this task is standalone TN positioning. Testing will primarily rely on simulations.

Assumptions: LEO satellites will be assumed with transparent or regenerative payloads. Additionally, availability of wideband positioning pilots (e.g., up to 400 MHz) and time-frequency resources will be assumed. Accurate knowledge of LEO satellite position and velocity will be assumed. Coordination and precise synchronization between the UE, NTN, TN, and RIS will be assumed. One or more positioning technique(s)/positioning measurement(s) will be utilized. Processing will be performed at the UE side or at the network side.

9.1.2 Integrated communication and monostatic sensing

Introduction: High frequency bands such as mmWave and sub-THz offer substantial bandwidth that enables high resolution delay estimation for radar, and high data rate for communication. Moreover, the need of high directivity antenna to achieve a satisfactory link budget offers two advantages. The first is improved angular resolution for sensing, and the second is the facilitation of spatial isolation. As a result, the implementation of monostatic radar becomes feasible, for instance by placing the radar receiver behind the transmitter [PBN+21]. For applications that require both functionalities, the available bandwidth can be shared in a JCAS system. The frequency resource allocation is determined based on the application requirements. In conventional radar processing, contiguous bandwidth is needed. Consequently, the radar performance could be compromised when the spectrum is shared. However, by employing interleaved allocation and multiband super-resolution algorithms, the radar performance can be maintained [LNS+22].

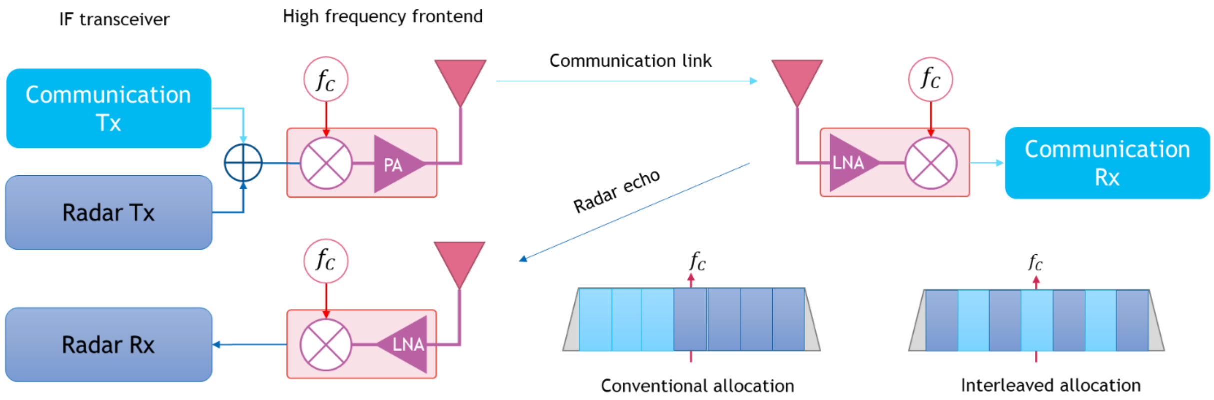

Figure 9-3 Integration of monostatic sensing and communication by sharing a large band.

Description: Figure 9-3 illustrates the concept of integrating communication and monostatic radar. A device aims at transmitting data to another device, in the downlink, and simultaneously perform sensing by processing the reflected signal. The baseband signal is generated by multiplexing the communication signal and the radar probing signal. In addition to spectrum allocation, power loading can be considered. The baseband signal is upconverted to high frequency and transmitted using a high frequency frontend. The radar receiver frontend receives the echo signal and down-converts it to baseband. The radar baseband receiver operates on the spectrum bands allocated for radar. Depending on the allocation and performance requirements, different algorithms can be utilized. The concept can be extended to accommodate multiple users by adopting hybrid beamforming. In addition to leveraging existing systems, the design of high frequency radio transceiver for JCAS will be considered to optimize performance. This is particularly important when aiming for ultra-high data rates and high-resolution sensing, as discussed in [HEX22-D22] and [HEX23-D23].

Use cases: This system is applicable to a wide range of applications that require high resolution sensing and/or high data rate communication. This is relevant to the "Fully merged cyber-physical worlds" use case. For instance, the radio can be exclusively used with full bandwidth allocation to achieve the data rate required for holographic communication. Alternatively, the same radio can be dedicated to pure sensing applications, such as gesture recognition for interacting with the environment. Additionally, the frequency resources can be shared between sensing and communication. This is particularly useful in scenarios such as using a VR headset to communicate contents, and at the same to perform sensing. The sensing capability in this context is crucial for safety, as it helps detect obstacles and protect users from physical harm.

KPIs and KVIs: The radio design will be tailored to meet extreme requirements for individual communication and sensing, including data rate, coverage, reliability, sensing accuracy and resolution. When considering both functions simultaneously, trade-offs will be made among a group of reduced KPIs. In terms of sustainability, the radio design will incorporate strategies to reduce the hardware cost and provide flexibility to save power by deactivating unneeded HW resources. During operation, the available resources will be efficiently utilized to optimize the signals and receive algorithms to reduce the overall energy consumption and maintain compliance with international and EU recommended EMF limits. This system can be leveraged for accurate sensing of the environment, where the gathered information can be exploited to enhance the reliability of communication, as well as for security and safety measures. Moreover, the same radio can be used for multiple purposes bringing new services to end users.

Benchmark: The proposed system will be compared with radar-centric such as frequency modulated continuous wave (FMCW) radar, and communication-centric radio design such as 5G mmWave. The comparison will consider performance, HW cost, and energy efficiency. Additionally, the optimized waveforms and signal processing schemes will be compared with the state-of-the-art (SOTA) approaches. These include, comparing super-resolution performance and complexity with cross-correlation, multiband sensing with a single contiguous band sensing, and evaluating optimized communication waveforms against OFDM-variants.

Assumptions: Two scenarios are considered. The first is based on reusing existing communication systems, such as mmWave, in the implementation. Here, the emphasis on optimizing resource allocation and signal processing. The other scenario concentrates on optimizing radio design with the dual requirements of sensing and communication. Initially, ideal hardware will be assumed. However, later considerations will include the potential impact of hardware non-idealities.

9.1.3 Integrated monostatic and bistatic sensing

Signals at mmWave frequencies offer numerous advantages for sensing applications due to their unique geometrical connections to physical propagation channels. Moreover, large bandwidth and large antenna arrays provide high delay and angle resolutions, allowing high-accuracy sensing performances. In mmWave sensing, monostatic and bistatic sensing are two commonly used modalities, and each may have its own strengths and weaknesses. These modalities are typically analysed separately, but by integrating them, the strengths of each can be leveraged to improve sensing performance. For instance, monostatic sensing can provide additional information about the environment that may not be available through bistatic sensing alone. The integration also allows us to better manage the uncertainties associated with landmark detection and user positioning, resulting in more accurate and reliable sensing. In this work, the focus is on developing efficient algorithms for the integration of two sensing modalities.

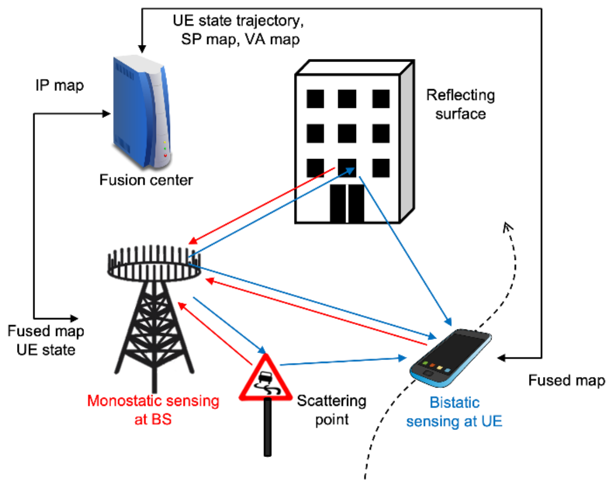

Figure 9-4 The integration of monostatic sensing and bistatic sensing. Monostatic sensing is performed at the base station, bistatic sensing is performed at the user, and the integration is performed at the fusion centre.

Description Figure 9-4, based on [GKS+23] provides an overview of the integration of monostatic sensing and bistatic sensing. Monostatic sensing involves the transmission of signals by the base station, which propagate through the complex environment and are subsequently received by the same base station to be used for sensing purposes. In contrast, bistatic sensing involves the transmission of signals by the BS to a receiver, which undergoes propagation through the environment and is eventually received by the user. This information is then utilized for sensing. Two extended Kalman-Poisson multi-Bernoulli sequential filters ([GKK+22]) are implemented to solve the sensing problems at the base station and the user, respectively. To enhance sensing performance, algorithm will be proposed that periodically fuses maps and user states from two modalities at the fusion centre. Then, the individual maps and UE states are overwritten with the fused map and UE state.

Use cases: Use cases include network trade-offs for minimized environmental impact (energy optimized services), immersive smart city, and interacting and cooperative mobile robots.

KPIs and KVIs: The relevant KPIs for positioning are positioning accuracy of the UE, while for sensing the mapping performance is measured in terms of the estimation errors, miss detections, and false alarms, between the true and estimated maps for different types of landmarks. In terms of KVIs, the enabler improves trustworthiness (fusing two independent sources of information is more robust and reliable).

Benchmark: The benchmarks are: (i) monostatic sensing without periodic fusion, and (ii) bistatic sensing without periodic fusion. Two cases are compared with the benchmarks, which are (i) monostatic sensing with periodic fusion, and (ii) bistatic sensing with periodic fusion. The periodic fusion is expected to improve the mapping and positioning performances of both two sensing modalities.

Assumptions: It is assumed that each landmark can create at most one path at each time step. Multiple bounce signal paths are ignored. The presence of sensing pilots is assumed, as well as the presence of a reliable link to fuse monostatic and bistatic sensing information.

9.1.4 Multi-static sensing

Conceptually, the simplest form of radar sensing is the monostatic radar where the transmitter and the receiver are collocated. However, in practice, the implementation of a monostatic radar is challenging mainly because of the usually required full duplex operation. Also, the performance of monostatic radar is limited by its ability to form LoS between itself and a target. An approach to alleviate the previous limitations is via the introduction of multi-static radar sensing, where multiple geographically separated nodes form a sensing system. Figure 9-5 illustrates schematically the extension of monostatic, bistatic, and MIMO radar sensing to its multi-static counterparts.

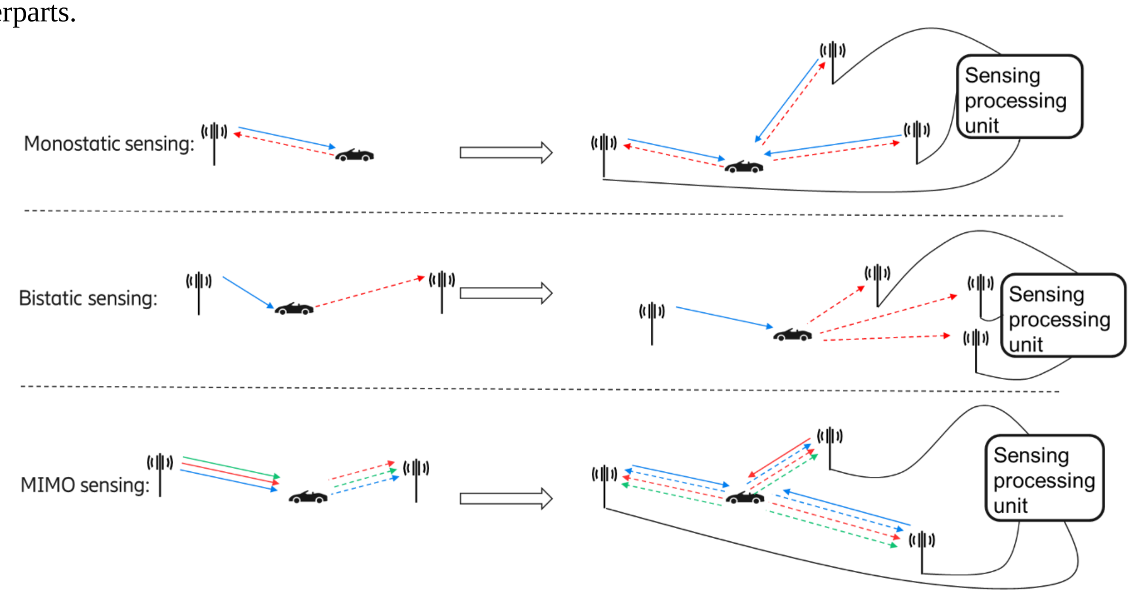

Figure 9-5 Illustration of the extension of monostatic, bistatic, and MIMO radar sensing to its multi-static counterparts.

Description: An approach for overcoming some of the limitations and challenges of monostatic radar sensing is via the introduction of additional sensing nodes, i.e., multi-static radar sensing. Different forms of multi-static sensing are shown in Figure 9-5, where the counterparts multi-static sensing for the cases of monostatic, bistatic, and MIMO radar sensing are depicted. Against this background, the aim is to explore the potential of multi-static radar sensing when it is composed from multiple bistatic radar sensing.

Use cases: The considered multi-static sensing relies on the use of one transmitting node and multiple receiving nodes. It is possible map the considered enabler to use case where there is a transceiver with one transmitting point and multiple receiving points. Therefore, the current enabler can be beneficial for the use cases of: a) digital twins for manufacturing, b) immersive smart city, c) fully merged cyber-physical world, and d) interacting and cooperative robots.

KPIs/KVIs: The current enabler aims to improve the target positioning in the 3D space. Also, it aims to improve the KVIs of inclusion and trustworthiness via the enhancement of the sensing coverage and accuracy, respectively. Also, improved sustainability is expected to be attained through the automation of the physical infrastructure obtained using sensing of high quality.

Benchmark: The considered benchmark is the corresponding performance of a single bistatic radar sensing.

Assumptions: The proposed enabler assumes the use of an OFDM waveform. Furthermore, perfect synchronization is assumed between the involved node, while the receive processing is done centrally in the sensing processing unit.

9.2 JCAS waveforms, frame structures, and resource allocation

JCAS can use the communication waveforms with different levels of knowledge, including dedicated pilots, known data, as well as unknown data. In this section, different waveforms and frame structures are considered with different levels of knowledge, considering monostatic, bistatic and multistatic JCAS.

9.2.1 Flexible baseband transceiver for JCAS

One aspect of JCAS involves the reuse of radio infrastructure, including RF frontends and processing resources for both sensing and communication functions. On top of that, radio resource allocation and signal processing solutions can be designed in a flexible way to serve wide range of applications. This application could purely involve data transmission, purely sensing, or a combination of both, operating simultaneously, such as AVs in industrial environments. Therefore, a flexible baseband transceiver is needed, that can adapt the transmission parameters, including waveforms [NLC+21], modulation and coding, and frame design and select the receiver algorithms depending on the scenario [BCN+21]. This adaptability introduces a trade-off between performance and other metrics, such as complexity and energy consumption.

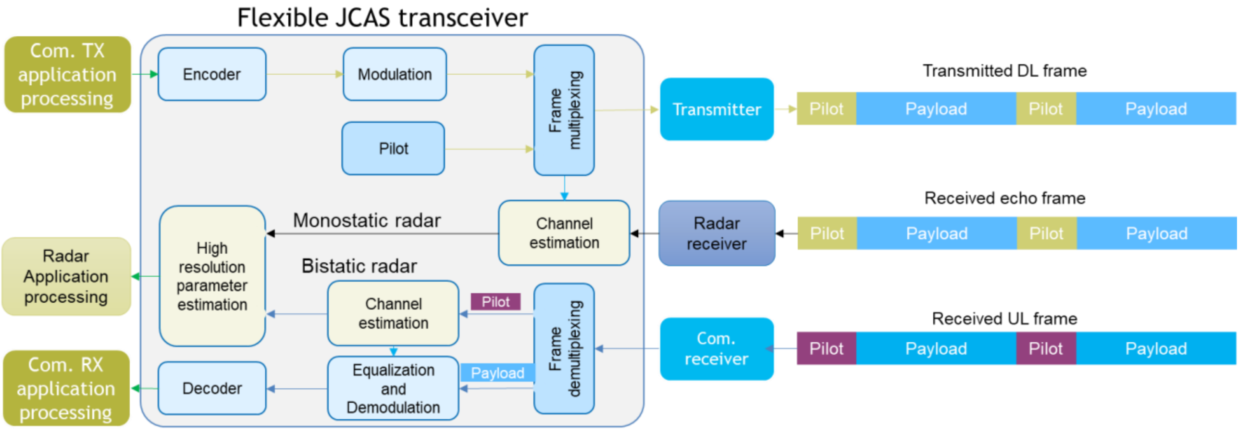

Figure 9-6 Flexible JCAS transceiver architecture, considering general monostatic and bistatic radar.

Description: The flexibility of the baseband transceiver can be customized according to the sensing architecture, frequency band, and the duplex mode. As a general case, the considered scenario assumes baseband transceiver for base station operating with an FDD mode, incorporating both monostatic sensing in DL and bistatic sensing in UL. As illustrated in Figure 9-6, the transmitted frame in DL consists of communication payload and pilots. A corresponding echo frame is received by a dedicated receiver frontend, operating with the same DL band. Additionally, an UL frame is received by a dedicated UL communication receiver. The flexibility of the transmitter allows for adjusting the parameters of the payload (i.e., modulation, coding, and waveform), the pilot signal, and the overall frame structure. At the communication receiver, the selection of equalization and decoding algorithms involves a trade-off of complexity and BER/BLER performance. Moreover, the sensing receiver has the capability to operate in different modes using various signals and different parameter estimation algorithms. For instance, it can operate using only pilot signals, or it could use the full frames, in addition to the possibility of fusing UL and DL signals. Algorithms include simplified cross-correlation based, or super-resolution approaches. These options provide a trade-off between complexity and sensing accuracy, where less processing power is needed at lower complexity.

Use cases: The use of flexible JCAS transceiver is particularly relevant in scenarios that involve diverse communication and sensing, as well as highly dynamic environment, where the transmission needs to be adapted according to the context. An example of such use cases is "interacting and cooperative mobile robots", discussed in Section 2.3.1. This use case involves heterogeneous devices with varying communication requirements, such as URLLC with a low data rate for robot control. The control could be for static robots or mobile AGVs. Additionally, high data rate communication is necessary for AR/VR interfaces used for human-machine interaction. Moreover, varying degrees of sensing accuracy are needed for different objectives, such as positioning, detecting obstacles to prevent accidents, predicting blockage, detecting human presence for safety, identifying interference and jamming. This use cases encompasses a variety of tasks, like several mobile robots collaborating on carrying goods, static robots cooperating in a production line, or human-robot interaction for training purposes. The flexibility of JCAS transceiver can be exploited in two ways, the first by configuring the transceiver in advance based on the intended task. The second approach considers adapting the frame structure dynamically during runtime to respond to changes in the environment.

KPIs and KVIs: The targeted KPIs values are context-based, to achieve the required link data rate, latency, reliability in terms of BLER. The relevant sensing KPIs include sensing accuracy, sensing resolution, and detection probability. A trade-off between performance and complexity is also considered. Flexible transceiver aims at efficient usage of resources considering KVIs for sustainability and trustworthiness to reduce energy consumption and improve system resilience by maintaining the service via adaption to environmental conditions. In addition, flexible JCAS allows serving wide range of devices, which contributes to inclusion.

Benchmark: The performance of flexible JCAS transceiver will be compared with a dedicated transceiver for individual sensing and communication function in terms of performance, required radio resource and hardware resources, and energy efficiency. Moreover, adapted frame structure and waveform will be compared with standard system with fixed waveform and frame structure, such as 5G NR.

Assumptions: The flexible JCAS transceiver is considered at BS side with FDD mode for communication. The BS is equipped with radar receiver that listens to the echoes in the DL band, and it is ideally isolated from the communication transmitter. Moreover, the initial state of the network is knowns, including number of devices and their initial location of devices, and the initial channel. Furthermore, ideal synchronization is assumed among all the network nodes.

9.2.2 Waveform learning for JCAS

In future wireless generations the design of hardware is expected to become an increasingly challenging task [SMM19]. Hardware impairments can degrade system performance and increase system design complexity. In recent years, ML approaches have been explored to overcome those limitations [DA23]. They rely on training data and do not require knowledge of the system model to optimize performance. However, deep learning often lacks interpretability and requires extensive amounts of data to train. Model-driven learning [SWE+23] has been proposed as an alternative that uses the knowledge of the system model, but replacing the components subject to impairments by networks that can deal with them. Additionally, they can be initialised from a reasonably good starting point. Model-driven learning has already found some applications in communications [BC19], [YL22] and JCAS [HEX22-D32, Section 3.2.2], [MHK+22].

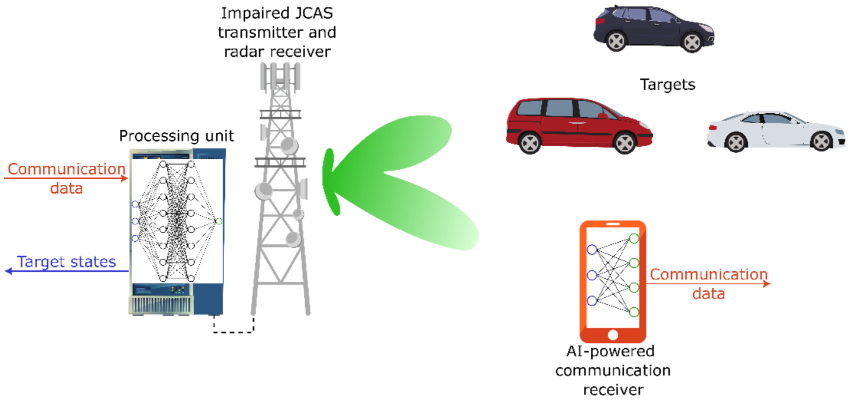

Figure 9-7 Schematic diagram of the considered JCAS scenario. The transmitter and the communication receivers are endowed with neural networks that can be optimized to deal with hardware impairments. Image designed using assets from Freepik.com.

Description: The JCAS scenario is depicted in Figure 9-7. The goal is to estimate the targets states (namely: detection probability and position estimation) and retrieve the transmitted communication message, under the effect of hardware impairments in the JCAS transmitter. A uniform linear array (ULA) at the transmitter and

OFDM signals are considered to perform such tasks. A model-driven neural network is considered in the transmitter side to produce an optimal beam and to later estimate the targets states. The communication receiver is not considered to be affected by impairments since it receives CSI from the transmitter. The model-driven approach is compared with a deep learning approach, where the entire transmitter is replaced by deep neural networks.

Use cases: The introduction of end-to-end learning in JCAS could significantly boost its performance, enabling the exploration of exciting new functionalities, including "immersive smart cities" and "Network trade-offs for minimized environmental impact (energy optimized services)". By integrating JCAS devices into road facilities, a comprehensive 4D map of the environment can be obtained, offering valuable insights for utilities management, such as optimizing public transport systems. Moreover, real-time data collected from cities can be effectively shared with the public, allowing for efficient tracking of traffic congestion and crowd gatherings. Strategic placement of JCAS devices also supports infrastructure monitoring and maintenance, thereby promoting the development of sustainable city models.

KPIs and KVIs: For sensing, the KPIs are sensing accuracy (RMSE between the true and estimated positions), detection probability (probability of correct detection of a certain number of targets) [RGS17], and complexity, measured as the number of real parameters of the involved neural networks. For communication, the KPI is the BER. The enabler relates to KVIs of sustainability (since accounting for impairments allows for less transmitted power to meet the same performance as standard approaches. Model-driven learning reduces even more the computational complexity of the system) and trustworthiness, since model-driven AI design provides interpretability in case of failures, compared to standard deep learning.

Benchmark: Three benchmarks are designed to compare with AI-learning: (i) transmitter benchmark, (ii) radar receiver benchmark, (iii) communication receiver benchmark. Benchmarks and AI methods use the same architecture in Figure 9-7 to combine radar and communication waveforms to obtain JCAS trade-offs. Under ideal conditions, AI approaches and the benchmark are expected to have the same performance. However, when impairments are introduced, AI methods are expected to considerably outperform the benchmark.

Assumptions: It is assumed that a general area where the targets and the communication receiver may be located is known by the transmitter. It is also assumed that the radar channel is differentiable, and that some channel state information is given to the communication receiver by the transmitter. Predefined targets are needed for training, which can be detected through possible camera (or other sensor) measurements.

9.2.3 Optimization of OFDM-based bistatic sensing

Bistatic sensing avoids the full duplex operation that usually is required in monostatic sensing. Also, in a cellular network, the presence of multiple nodes enables the convenient selection of pair of nodes which improves the performance of bistatic sensing. Given that OFDM and its discrete Fourier transform (DFT) pre-coded variant, i.e., DFT Spread-OFDM (DFTS-OFDM), is the waveform upon which 5G NR is build, it is likely that also the 6G will be based on OFDM for at least a portion of the spectrum where it will be used. Therefore, bistatic radar sensing using OFDM appears as a strong candidate for JCAS in 6G.

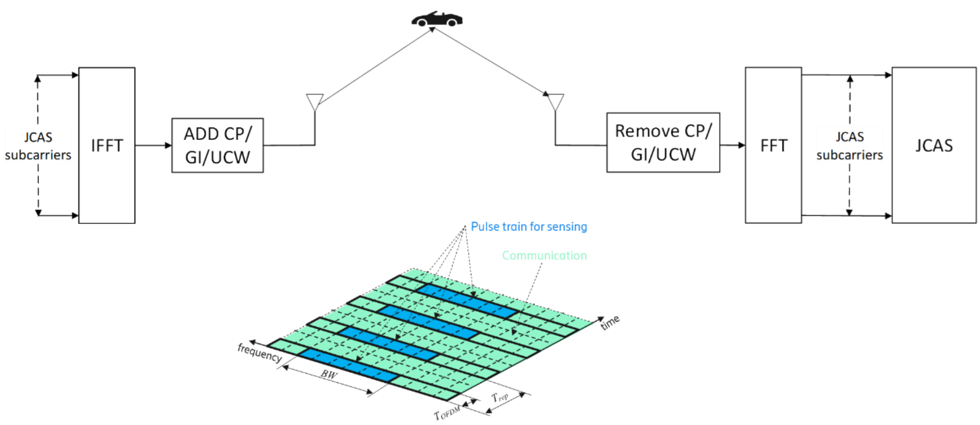

Figure 9-8 Schematic Illustration of bistatic radar sensing when the used waveform is based on OFDM along with an example of a possible resource allocation in the time-frequency grid.

Description: The operating principle of OFDM-based bistatic radar sensing is given schematically in Figure 9-8. Apart from transmit and receive beamforming, the main mechanism for controlling the performance of OFDM-based radar sensing, for a given numerology, is the resource allocation in the time-frequency grid. Therefore, it is important to study the inherent trade-off between the selection of the used numerology, allocation of sensing and communication resources in OFMD symbol level and frame level, and the communication and sensing performance under realistic assumption of channel modelling and beamforming.

Use cases: The used waveform and way that the communication and sensing signal are structured in the available radio resource determine in large extent the performance of a JCAS system. Therefore, this enabler is relevant to the following use case: a) energy optimized services, b) digital twins for manufacturing, c) immersive smart city, d) fully merged cyber-physical worlds, and e) interacting and cooperative mobile robots.

KPIs/KVIs: The current enabler aims to improve the sensing performance while reusing existing communication circuity. Also, it aims to improve the values of sustainability and trustworthiness via the enhancement of the sensing accuracy and via the reuse of existing circuitry and infrastructure.

Benchmark: The considered benchmark is the corresponding performance of OFDM bistatic radar sensing under idealistic assumptions of: i) channel modelling that considers multipath propagation and clutter and ii) beamforming with genie AoA estimation.

Assumptions: The proposed enabler assumes the use of an OFDM waveform with communication signalling, i.e., pilots and/or data. Furthermore, perfect synchronization is assumed between the transmitter and the receiver.

9.2.4 Resource allocation in multiband hybrid-beamforming transceiver

Hybrid beamforming is viewed as a viable architecture for operating with ultrawide bandwidth at high frequency bands, such as mmWave and sub-THz, as proposed in [HEX22-D22] and [HEX23-D23]. In this approached, the wideband is divided into narrower bands and multiband transceiver design is employed. Each band is connected to a transceiver chain and antenna array. Accordingly, various combinations of bands and beams can be allocated for communication with UEs or for performing sensing tasks. Resource allocation in this context refers to the problem of optimally assigning resources such as power and bandwidth across multiple bands and beam direction, with the goal to maximize the overall system performance. This includes considerations of various performance metrics for both communication and sensing, in addition to energy efficiency, among others.

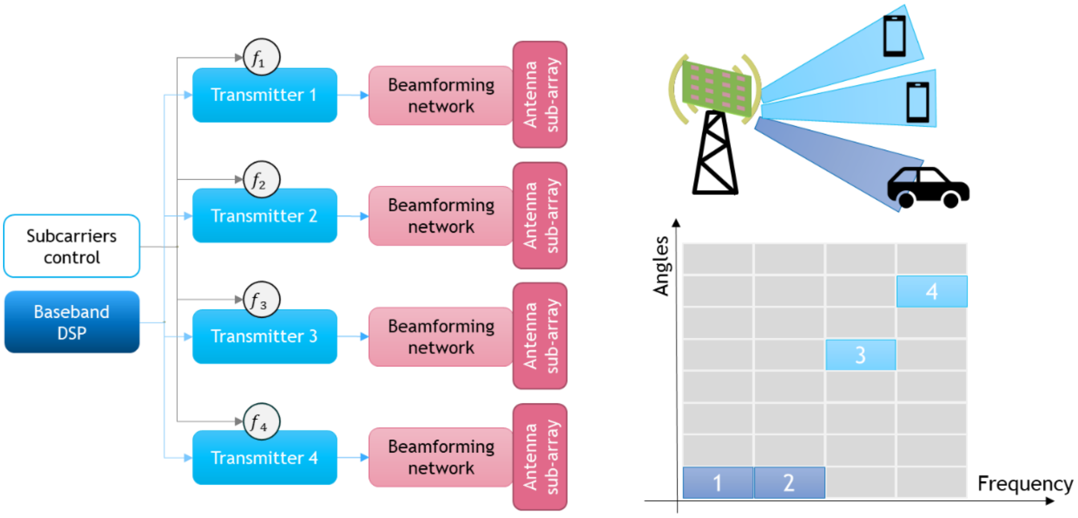

Figure 9-9 Hybrid beamforming transmitter and corresponding angular-frequency resources.

Description: As depicted in Figure 9-9, an access point transmitter is composed of multiple signal chains. Each of these chains is connected to a beamforming network and subarray. Similar architecture is considered for the receiver. A chain can be calibrated to a specific carrier frequency and directed to a particular angular direction. This allows a variety of angular-frequency allocation schemes to serve multiple nodes with communication and/or sensing functions. For instance, high bandwidth for radar functions can be achieved by aggregating multiple bands in the same angular direction. Spatial division can be used to communicate with multiple users, where the same band is utilized at different angles. Alternatively, frequency division can be employed for serving multiple users in the same direction. The receiver on the device side can adopt a simplified architecture with fewer signal chains.

Use cases: This approach is particularly effective in use cases that involves multiple users and demand extra capacity. High frequency bands are ideally suited for dense deployment with short-range coverage, primarily due to their ability to carry high data rates over shorter distances and their inherent property of spatial isolation, which enables more simultaneous connections within a confined area. As an example, it can be used in some of the scenarios in the "Immersive smart cities" use case presented in Section 2.3.1. One such application could be providing high-speed, reliable access to users on the road, real-time traffic information, and navigation assistance in an intelligent transportation system. Additionally, variety of sensors and actuators are deployed to monitor and control various aspects of the city infrastructure. These devices may require different communication needs. Lastly, sensing is essential for smart cities to continuously monitor the environmental conditions. A multiband hybrid-beamforming transceiver is an enabler for these varying requirements by dynamically assigning the necessary resources.

KPIs and KVIs: Communications KPIs include per user data rate, range, reliability, and latency, whereas sensing KPIs includes angular accuracy, delay accuracy, velocity resolution and range. This enabler contributes to improving KVIs for sustainability and inclusion. Namely, an optimized resource utilization aims at improving the energy efficiency resorting to several approaches such as deactivating unnecessary chains or changing the waveform parameters. Moreover, optimizing the radio design aims at reducing cost for user devices. This could involve simplifying the radio architecture and using more cost-effective components. This is essential for making the technology accessible to a wide range of users.

Benchmark: The multiband transceiver architecture will be compared with a single-band transceiver, wherein the total bandwidth is processed through a single chain, and time division is used to serve multiple users, such as in 5G mmWave system. The comparison will be conducted in terms of performance, and energy consumption.

Assumptions: The system operates in TDD mode, where the receiver at the access point is used for monostatic sensing in the downlink and for communication in the uplink. An ideal isolation between transmitter and receiver is assumed. Additionally, the transceiver chains can be reconfigured for both carrier frequency and beam steering. Prior to allocating the resources, the location of UEs should be known for communication, whereas for sensing, the allocation could be context-dependent. For example, an arbitrary environmental scan may be considered, or a specific direction should be utilized for tracking a predetermined target.

9.2.5 Resource allocation for 6D tracking in JCAS scenarios

Antenna arrays are expected to be adopted in future communication networks to combat the pathloss of the high-frequency signals [FSD+20]. In this case, resource allocation (e.g., beamforming at the BS) needs to consider not only the 3D position, but also the 3D orientation of the UE. Take Figure 9-10, for example, at least two BSs are needed for 6D localization (i.e., 3D positions and 3D orientation), which can further be used for improving communication performance (e.g., beamforming direction). Consequently, 6D localisation and tracking are needed to support JCAS resource allocation, which supports energy-optimized services.

Description: For an optimized JCAS resource allocation, three components are needed, namely, 6D localisation, 6D tracking, and resource allocation. 6D localisation: With positioning pilot signals transmitted from BS (downlink) or UE (uplink), the 6D state of the UE can be estimated in the presence of (i) multiple BSs [ZBC+22]; (ii) one BS and a RIS [CSB+22]; (iii) one BS with stable multipath components [NSJ+23]. 6D tracking: Due to the special property of the rotation matrix, which lies in a special orthogonal group in three dimensions (i.e., SO3 manifold), traditional filters can no longer be adopted directly. In this case, errors in the tangent space need to be considered, which can be benchmarked by intrinsic Cramér-Rao bound (ICRB) [Bou13]. Resource allocation: Analogue or hybrid structures are usually used (instead of a digital array) for large antenna arrays. Under this structure, beamforming optimization (i.e., precoder and combiner) is needed to improve the overall performance. Communication KPI-oriented [SLF22] and localisation KPI-oriented

[KJM+22] solutions have been investigated by researchers. However, the optimization strategy considering both KPIs under mobile scenario needs to be designed for JCAS systems.

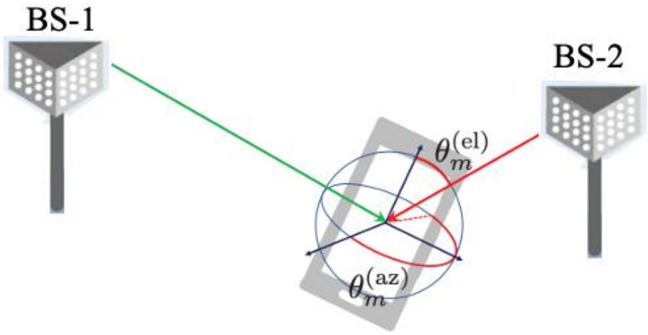

Figure 9-10 Illustration of 6D localisation (3D position and 3D orientation) for optimized JCAS resource allocation.

Use cases: In addition to 3D position, 3D orientation estimation is possible with an array equipped at the target/user. On the one hand, 6D states enable applications such as fully merged cyber-physical worlds (e.g., virtual reality, extended reality), interacting and cooperative mobile robots (e.g., human-machine interaction, drone deliverable), and so on. On the other hand, tracking of 6D states can assist in optimizing beamforming and resource allocation, leading to an energy-efficient network.

KPIs and KVIs: The main positioning KPIs include positioning accuracy, orientation estimation accuracy, while the communication KPIs is the achievable SNR. In terms of KVIs, the optimised beamforming will lead to reduced power consumption compared to benchmarks, thereby improving sustainability.

Benchmark: The benchmark for localisation and tracking algorithms will be Cramér-Rao bound (CRB) (for position) and ICRB (for orientation). The benchmark for optimization includes conventional random beams or directional beams. MATLAB simulator with analysis of system performance and simulation of developed algorithms are expected.

Assumptions: Pilot signals (uplink and downlink) are assumed for localisation with flexible time-frequency resources to be allocated. Furthermore, the channel requires multiple signal propagation paths, for example, in the presence of (i) multiple BSs; (ii) one BS and a RIS; (iii) one BS with stable multipath components.

9.2.6 Resource allocation and protocols for inter-UE sensing

The best sensing results can be obtained by utilizing a sensing setup that is suitable for a concrete application. Often, the sensing area is rather in the vicinity of end-user devices than close to a base station. Hence, architectures that enable monostatic and bistatic sensing utilizing one or multiple UEs are required. Key enablers for such setups are suitable resource allocation methods and protocols for inter-UE sensing.

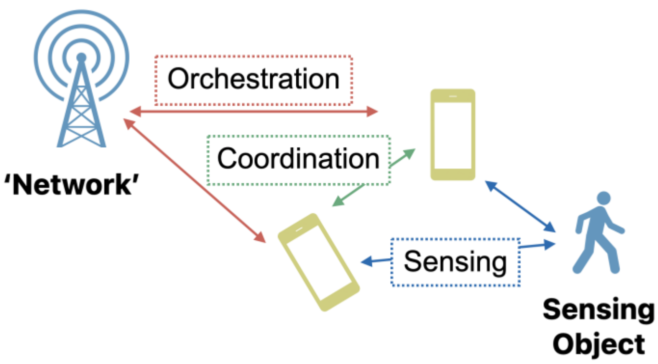

Figure 9-11: Schematic diagram of inter-UE sensing

Description: Figure 9-11 shows a schematic overview of involved parties for the inter-UE sensing use case. Several UEs will participate in the sensing activity, which will mutually coordinate their transition (or general) activity, orchestrated or supported by network information. The focus is on the design of resource allocation schemes and protocols for inter-UE sensing. The challenging part herein is to coordinate the inter-device sensing with communications. This requires new protocols and resource allocation schemes that will be developed within this enabler. Key questions relate to the exchange of data between nodes, what kind of data need to be shared, and whether privacy is affected. Furthermore, synchronization aspects between the nodes play a central role.

Use cases: The use cases 'digital twins for manufacturing', 'immersive smart city', 'fully merged cyber-physical worlds', and 'interacting and cooperative mobile robots can benefit from this enabler.

KPIs/KVIs: The performance is measured with all sensing-related KPIs, such as positioning accuracy, SNR, range resolution, Doppler resolution, sensing accuracy while maintaining a given communication performance. Furthermore, energy efficiency and power consumption need to be considered as well. The solution contributes to the trustworthiness of the system since the end user has better control over and insight to what is happening during sensing operations.

Benchmark: The performance will be compared against commonly investigated architectures such as bistatic sensing between base stations or between base station and UE. The protocols can be evaluated in terms of coordination and orchestration overhead and resource allocation is evaluated in terms of spectral efficiency.

Assumptions: The presence of sub-THz access.

9.2.7 Power consumption of JCAS

The use of JCAS will result in a growing number of applications that need much higher bandwidth than today. The use of mmWave radio (above 6 GHz, known as the 60 GHz band) will enable this, as it will enable multi-Gbps data rates, higher number and highly directional beams, and high spatial reuse. Such a situation will imply the need for new end devices but will also lead to higher power consumption. Different experimental studies have been performed to analyse and evaluate the power consumption of devices and systems considering the PHY data rates [SSK+17], [SDI+15] and channel width [HQG+12], application layer throughput [HQG+12], [SMD+16], and technologies [SPB+20].

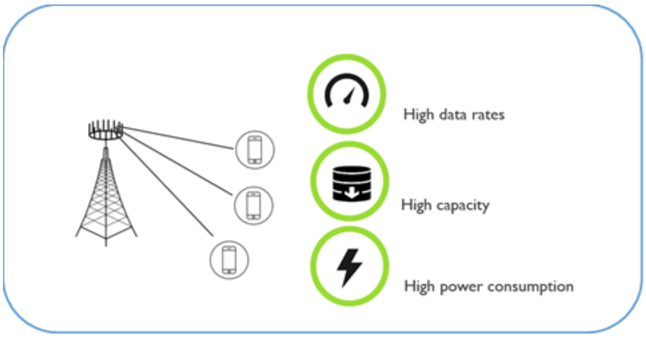

Figure 9-12 Schematic diagram of power consumption when using directional beams antennas.

Description: Considering the proposed use cases, the plan is to perform a detailed study of the power consumption of mmWave devices in different operating conditions and under different configurations. As shown in Figure 9-12, for beamforming mmWave devices with higher data rates and high capacity, the power consumption will be analysed. Existing analyses based on IEEE 802.11ad adapters will be extended with mmWave wireless technology. The planned experiments will include the considered device and a power analyser, where the different states include (i) power required to turn the device on while the radio interface is down; (ii) power consumption required to generate traffic when the radio interface is up; (iii) power consumption on and off beacon period; (iv) power consumption on the Transmission and Reception modes; (v) power consumption when changing Modulation and Coding Index (MCI); (vi) power consumption when changing propagation conditions (LoS, NLoS).

All above planned experiments will have in focus the type of gestures and the result on gesture recognition performance. Thus, the plan is to dynamically maximize the number of gestures and analyse the power consumption or energy budget required compared with accuracy constraints, detection probability, SNR, impact of the environment, etc.

Use cases: This work is relevant and applicable for "Fully merged cyber-physical worlds." use case in Section 4.4.2.
KPIs/KVIs: Power consumption and energy efficiency investigation for the respective considered situations and and its relation/impact on sensing KPI's (e.g., accuracy, detection probability, SNR, etc.). Relevant KVI for this enabler is Sustainability.

Benchmark: Power consumption results when using 802.11ad, WiGig, and WIFI (802.11ac).

Assumptions: Technical documentation of the chosen hardware will be considered to understand the power consumption of components that are unable to be measured using the current measurement setup.

9.3 JCAS security and privacy

The ability to accurately track both connected users and passive objects and the ability to enable safety critical applications raises security and privacy concerns. These will be addresses as described below.

9.3.1 Privacy and security for JCAS

Due to the sensitive nature of the information produced from a sensing procedure of JCAS system and the way that it can be used, the aspects of privacy and security are very important. In particular, a sensing procedure produces data for the actual physical environment that may trigger a change in this environment. Also, a sensing procedure can create data that traditionally belong to the private domain of an entity. Consequently, a JCAS system needs to consider security and privacy parameters that are beyond the ones considered until now by the existing communication networks.

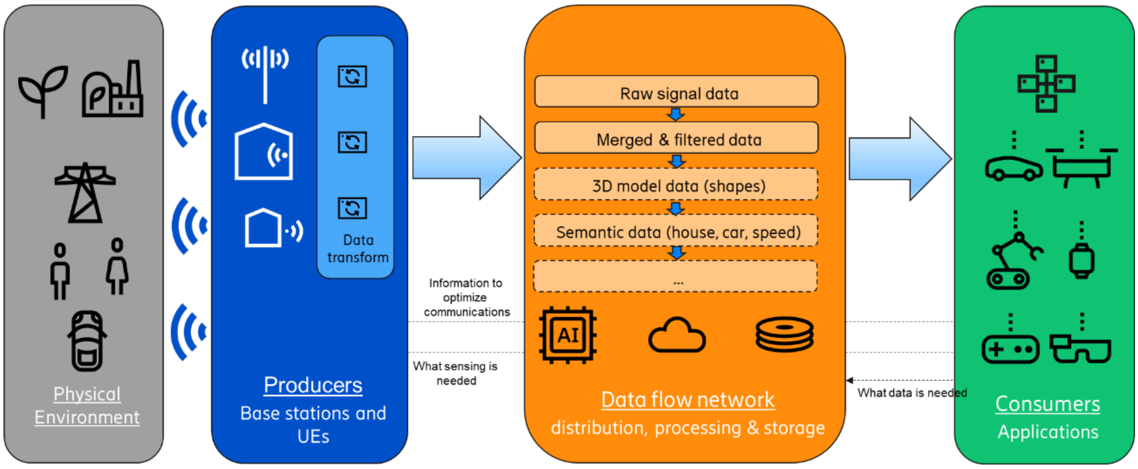

Figure 9-13 Schematic illustration of a JCAS system and the way its main elements interact with each other.

Description: Figure 9-13 presents the structure of a JCAS system and the way its basic elements interact with each other. As JCAS introduces the new functionality of sensing that is beyond communication, its impact in terms of security and privacy need to be characterized. In this study, the aim is to identify the security and privacy requirements between the different elements of a JCAS system. In addition, recommendations that improve the security and privacy of a JCAS system will be provided.

Use cases: Privacy and security are directly connected with the trustworthiness of a JCAS system. Therefore, the current enabler is beneficial to the use case of: a) e-health for all, b) digital twins for manufacturing, c) immersive smart city, d) fully merged cyber-physical world, and e) interacting and cooperative robots.

KPIs/KVIs: The identification of the KPI of this enabler is still to be determined. The current enabler aims to improve the KVI of trustworthiness.

Benchmark: The considered benchmark system is the security and privacy mechanisms adopted by the: i) IEEE 802.11bf standard that is related to sensing, and ii) conventional cyber-physical systems.

Assumptions: The main assumption under which the current enabler will be studies is JCAS in 6G deployments.

9.3.2 UE-related security aspects of JCAS

System improvements related to sensing not only enable new use cases but also make the system more vulnerable to attacks. Especially advances in multistatic sensing build upon tighter synchronization and the systems are expected to offer high resolution and accuracy in all domains. These advances may be exploited by malicious attacks or leaked to unintended consumers.

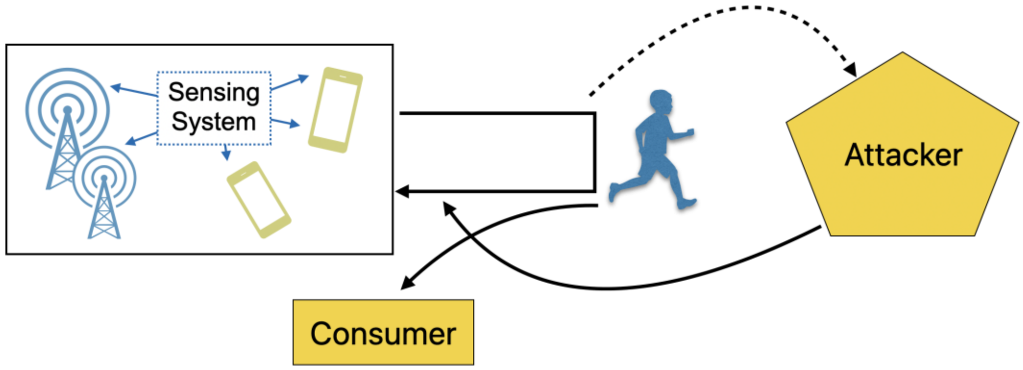

Figure 9-14: Schematic diagram for security aspects in joint communication and sensing systems.

Description: An analysis on security aspects in joint communication and sensing systems will be conducted (see Figure 9-14). The focus will be on the secure sensing part, as security aspects related to communication are generally understood. Attack schemes will be analysed by studying the attack surface of each sensing and communication link of the system. The analyse targets wireless signals that are used to sense objects and may contain sensed information after being reflected by a target. Finally, requirements on the JCAS system to minimize the attack risk will be derived.

Use cases: This enabler affects all use cases that can utilize sensing, including 'digital twins for manufacturing', 'immersive smart city', 'fully merged cyber-physical worlds', and 'interacting and cooperative mobile robots.

KPIs/KVIs: Security cannot be captured and evaluated with KPIs such as positioning accuracy, SNR, range resolution, Doppler resolution, and sensing accuracy. Security has rather to be seen as a fundamental requirement that all other solutions need to fulfil while delivering any of the above KPIs. However, it is the foundation for the KVI trustworthiness of the system since security lays the foundation for trust into sensing results and trust into ownership of any sensing data.

Benchmark: Legacy systems don't offer the capability to compare against.

Assumptions: Advances in 6G architecture definition will be considered.

9.3.3 Jammer localisation

Jammers can disrupt cellular networks by creating interference in the frequency bands used by the network. This interference can cause dropped calls, reduced data rates, and other disruptions, which can lead to customer dissatisfaction and revenue loss for service providers. By detecting and locating jammers, network operators can take measures to prevent or mitigate the effects of jamming and maintain network integrity. However, it is important to identify the signal of the jammer at multiple receivers.

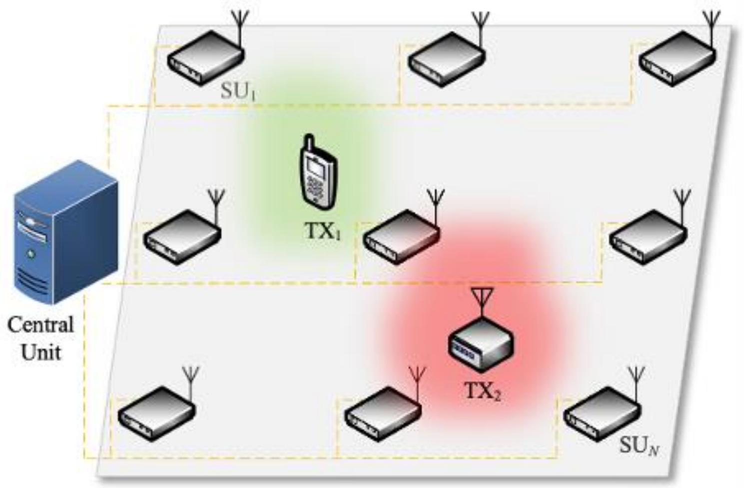

Figure 9-15 Jammer detection and localisation in a network of receivers, from [ACN+21].

Description To test the effectiveness of detecting and locating jammers, a testbed of software-defined radios called w-iLab.t (see Figure 9-15) will be used. This testbed allows for the emulation of actual cellular network waveforms, making it possible to test the detection and localisation of jammers under realistic conditions. The use of specific emitter identification (SEI) will be studied, to improve the localisation of jammers. SEI involves analysing the electromagnetic emissions of a jammer to identify unique characteristics, such as its frequency or modulation pattern.

Use cases: Jammer localisation can be a useful tool in the development of "digital twins for manufacturing" (Section 4.2.3.1 in [HEX21-D12] and Section 2.3.2 in [HEX22-D13]) facilities. By incorporating data from jammer localisation systems into digital twins, it may be possible to identify and mitigate the effects of jamming on the manufacturing process. The use of digital twins can in the future provide a platform for testing and validating new jammer detection and localisation techniques, which can then be implemented in the physical manufacturing environment.

KPIs/KVIs: Network's jammer location estimation accuracy (90%), jammer location estimation latency, jammer location estimation availability. The related KVI is trustworthiness, since detecting and locating jammers allows mitigating their effect.

Benchmark: Blind localisation in WSN without identification has been proposed in [ACN+21]. This is the benchmark for Hexa-X-II work for moving to real world scenarios and adding SEI.

Assumptions: Assumptions for detecting and locating jammers in cellular networks are based on the use of multiple spatially diverse antennas to receive the jammer signal [ACN+21], and specific emitter identification through unsupervised clustering techniques [WPZ+22].

10 Proof-of-concepts

Some components of the work described in the previous chapters are demonstrated in proof-of-concept implementations. The components to be demonstrated are:

- AI based air interface design
- Flexible transceiver design
- JCAS and sensing in a bi/multi-static configuration
- Channel characterization and channel model above 100 GHz.

The purpose of all the PoCs is to show that it is possible to run developed concepts on real hardware and thus take the technology readiness level (TRL) a step further. The different PoCs planned are outlined in more detail in the following sections.

10.1 AI-native air interface

This section describes the proof-of-concept (PoCs) which demonstrate the benefits of AI-native air interface. The first part presents the outline of a PoC that demonstrates how to obtain interoperable UE-side ML Model (also referred to as Encoder) and NW-side ML Model (also referred to as Decoder) for channel state feedback compression. This is a crucial aspect in creating practical two-sided AI algorithms in a multi-vendor network. In the second part another two-sided model is shown, where the transmitter and receiver are trained end-to-end without any pilot overhead.

10.1.1 ML-based channel state feedback compression in a multi-vendor scenario

Experimental Setup: This contribution aims to establish ML CSF feasibility between the BS and the UE in real world with multi-vendor training. The details of this enabler are given in Section 6.3.2.1.

A joint training approach requires sharing Neural Network (NN) model structures during the training process and is thus not desirable for multi-vendor scenarios. Instead, for multi-vendor training, it is proposed to only exchange data. As such, the NN models can be trained by each party without disclosing the implementation architectures. Description of steps of sequential training process is illustrated in Figure 10-1.

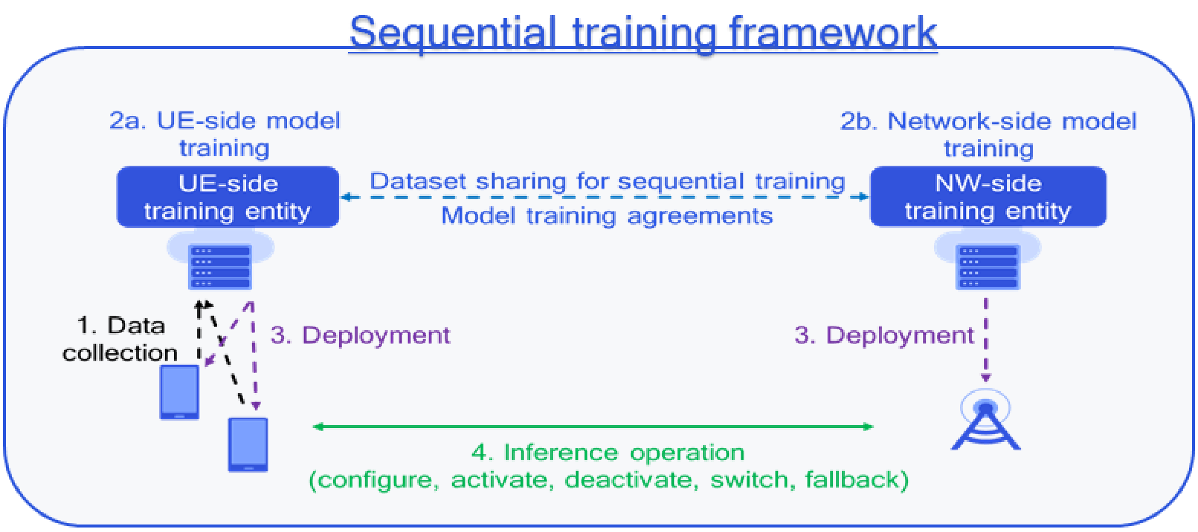

Figure 10-1: Illustration of the sequential training process.

As shown on the figure, the UE starts by collecting channel state measurement (Step 1: data collection) and then trains a ML model Encoder for CSF compression, this is step 2a: UE-side model training.

After UE-side model training, the UE shares a dataset to the network containing compressed CSF-samples and the channel state inputs, i.e., the ground truth, samples for sequential training. With this dataset, the network trains a ML model capable of decoding the compressed CSF (step 2b. Network-side model training). After training, the UE-side and NW-side ML models are then deployed to the UE and the BS, respectively (Step 3: Deployment).

With multiple UEs, the NW would gather data sets from the different UEs to train a single, common, ML-model that supports different encoder models from different vendors.

Measurement Scenarios: As mentioned in Section 5.3.2, a massive MIMO configuration is considered with operation in FR1 band and in TDD mode.

The KPI for this POC is the demonstration of inter-operability between different vendors to enable X-node ML CSF. Specifically, the KPI considered for performance comparison is SGCS loss for CSI accuracy. That means measuring the SGCS of the input channel state eigenvector versus the (decompressed) eigenvector of the estimate channel state at gNB.

10.1.2 Pilotless operation with a partially learned air interface

Experimental Setup: The primary target of this contribution is to demonstrate the practical feasibility and performance gains of an ML-based pilotless air interface. The PoC is depicted in Figure 10-2 where the highlighted blocks represent the learned elements. This PoC is a SISO variant of the approach described in Section 6.3.1.

In the first phase, the models are trained in a simulator, which has been configured based on the use cases of interest. Once the performance of the models is satisfactory in the simulator, they can be deployed on to the target PoC hardware. The PoC is based on a GPU-based implementation of 5G L1, where some of the functions can be replaced with pre-trained ML models (in this case, the constellation shape and the receiver algorithms are replaced). This makes it also possible to compare the performance of the ML-based air interface to a corresponding 5G air interface, using the very same hardware.

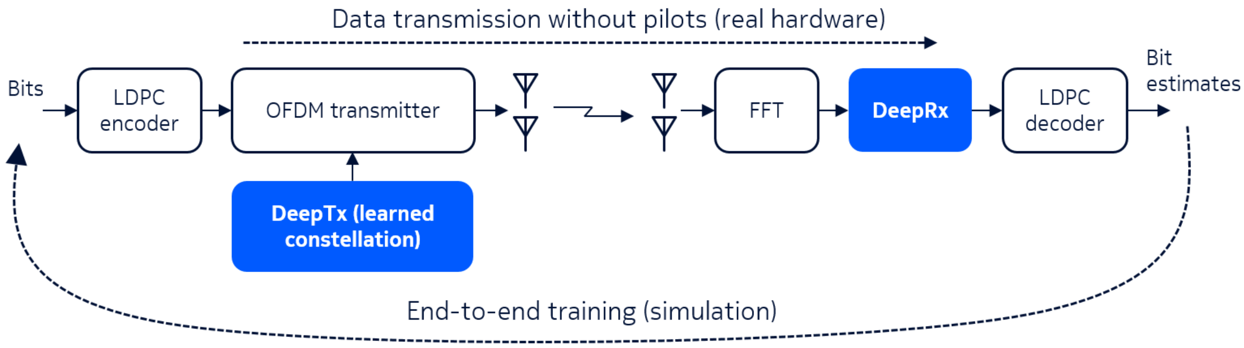

Figure 10-2: AI-based pilotless proof of concept.

The main KPI of this PoC is the link throughput, the target being that the ML-based PoC outperforms the 5G baseline. The primary mechanism for achieving this is the reduced overhead, as the learned system does not require the use of channel estimation pilots.

Measurement Scenarios: The PoC will be evaluated under a wide range of scenarios, using either a channel emulator or OTA transmissions. The former allows for convenient testing even under high velocities, whereas the OTA measurements will confirm that throughput gains are achievable with real-world physical channels.

10.2Flexible modulation and transceiver design

This PoC aims at demonstrating different level of flexibility in the radio design. As depicted in Figure 10-3, the transceiver comprises three flexible modules:

1- **Digital baseband:** This provides flexible transmission and detection schemes. It can be implemented on various processing platforms, such as general-purpose CPU, DSP, and filed programmable array (FPGA). The digital baseband at the transmitter performs coding, modulation, waveforms, and precoding, providing IQ samples to DFE of the IF transmitter. At the receiver side, the digital baseband receives IQ samples from the receiver DFE, and it performs equalization, demodulation, and decoding.

2- **Flexible IF transceiver:** This consists of multiple RF chains operating at IF frequencies. Each transmitter chain includes a DFE that provide IQ samples to two DACs and performs up-sampling, interpolation, and digital filtering, in addition to other functions used to compensate for hardware impairments, such as IQ imbalance, DPD for PA. After lowpass filtering (LP), the analogue baseband signal is upconverted to an IF signal via quadrature amplitude modulation and then amplified by PA. The IF receiver consists of LNA, QAM, LP, ADCs. The IQ samples at the output are fed to the receiver DFE for filtering, dissemination and down-sampling. The DFE is implemented on FPGA, and it provides runtime flexibility in configuring the sampling frequency. Moreover, due to the FPAGA flexibility, the signal processing functions can be reconfigured depending on the frontend hardware. The receive DFE may also implement synchronization functions. In addition to flexibility of FDE, the IF transceiver allows the configuration of the IF carrier frequency per chain and the number of active chains.

3- **RF frontend:** The IF signals from the IF transmitter can be utilized in various ways to feed different types of RF transmitters. In its simplest form, the RF frontend can be an array of antennas connected to the output of each chain. Alternatively, the IF signals can be combined and fed to a single antenna. The RF frontend can include high frequency extender. Similarly, the receiver frontend can be an array of antennas, or comprises high frequency extenders.

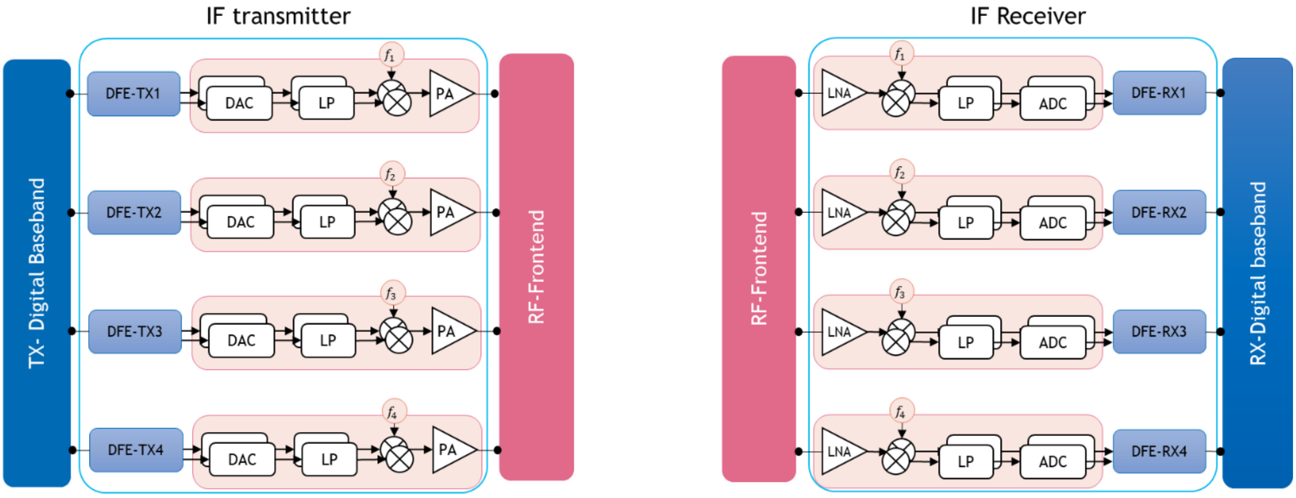

Figure 10-3 Flexible transceiver architecture.

The implementation of the IF transceiver is based on SDR platforms. The digital baseband implementation can be in software for performing hardware-in-loop (HIL) evaluation, or on FPGA for real-time demonstration. Different RF frontends can be integrated, depending on the operating frequency bands, such as sub-6 GHz, mmWave, and sub-THz.

This flexible architecture will be exploited to demonstrate several aspects, including the implementation of Gearbox PHY with multiple gears, and the demonstration of flexible baseband transceiver and resource allocation for JCAS. Two configurations will be the focus: ultrawideband analogue multicarrier, and hybrid beamforming.

10.2.1 Ultrawideband analogue multicarrier configuration

As illustrated in Figure 10-4, ultra-wideband can be divided into multiple subbands, and each can be transmitted on different frequency by tuning the transmitter chain frequency. The IF signals are combined to form an ultra-wideband signal, which is transmitted OTA using a single-input RF frontend. The receiver follows a similar structure, but replaces the combiner with a splitter. The subbands can be separated and isolated such that each of them can operates as an independent channel.

This demonstration aims to illustrate the concept of Gearbox PHY presented in Section 3.1.1, where the gear can be defined by the number of active signal chains.

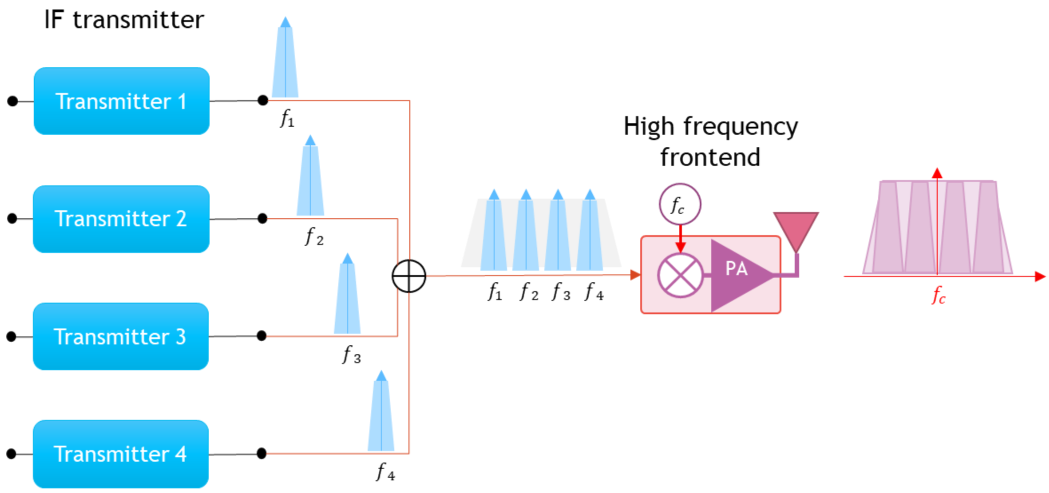

Figure 10-4 Analogue multicarrier for integration with high frequency and ultrawideband frontend.

An implementation of this scenario is shown in Figure 10-5, illustrating transmission over 140 GHz channel. An ultra-wideband OFDM signal can be also generated by this setup. However, it requires precise synchronization among the subcarriers.

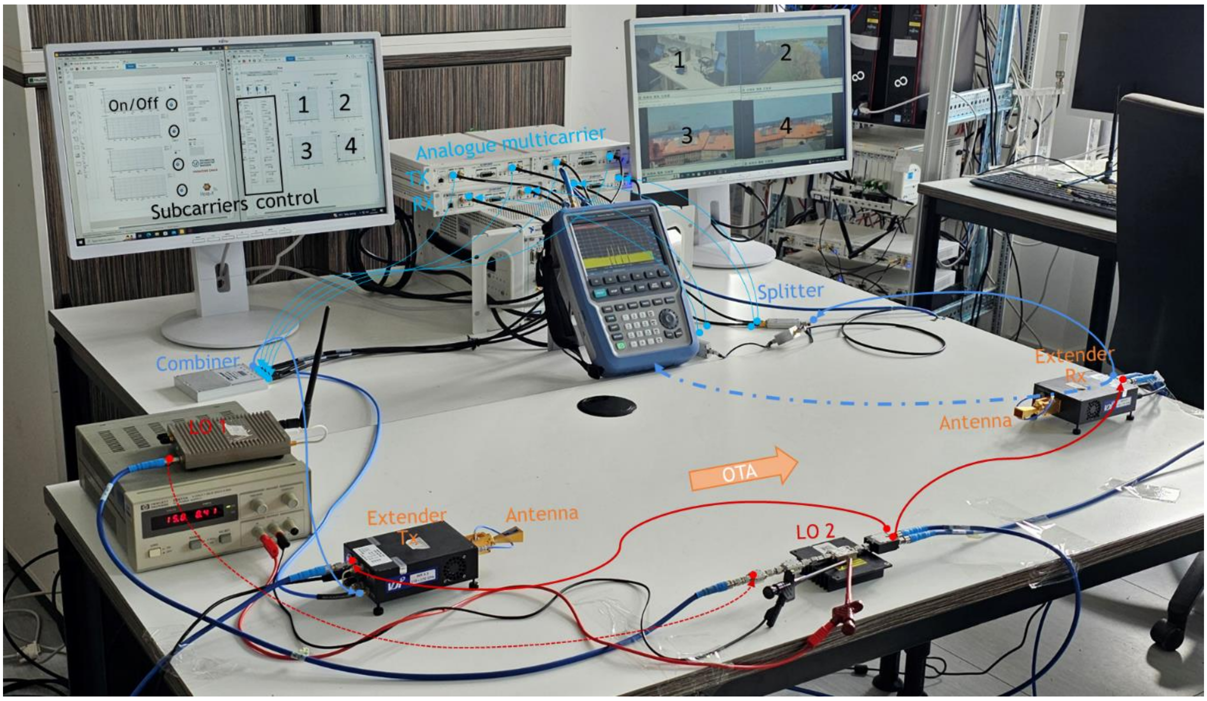

Figure 10-5 Implementation of analogue multicarrier with SDR platform and sub-THz frequency frontend.

10.2.2 Hybrid beamforming configuration

This demonstration will focus on resource allocation in multiband hybrid-beamforming transceiver presented in Section 9.2.4.

In this scenario, as depicted in Figure 10-6, the output of each chain in the IF transmitter is connected to an antenna subarray with beam-steering capability, the receiver follows a similar setup, employing as subarray beamforming at the input of the IF receiver. The capability to configure the carrier frequency and the angle for each chain allows for effective management of the angular-frequency resource grid. This can be exploited in JCAS, where some resources are allocated for sensing function, while others are dedicated to communication. The baseband modules in this scenario allows performing digital precoding for additional freedom in controlling the beam direction.

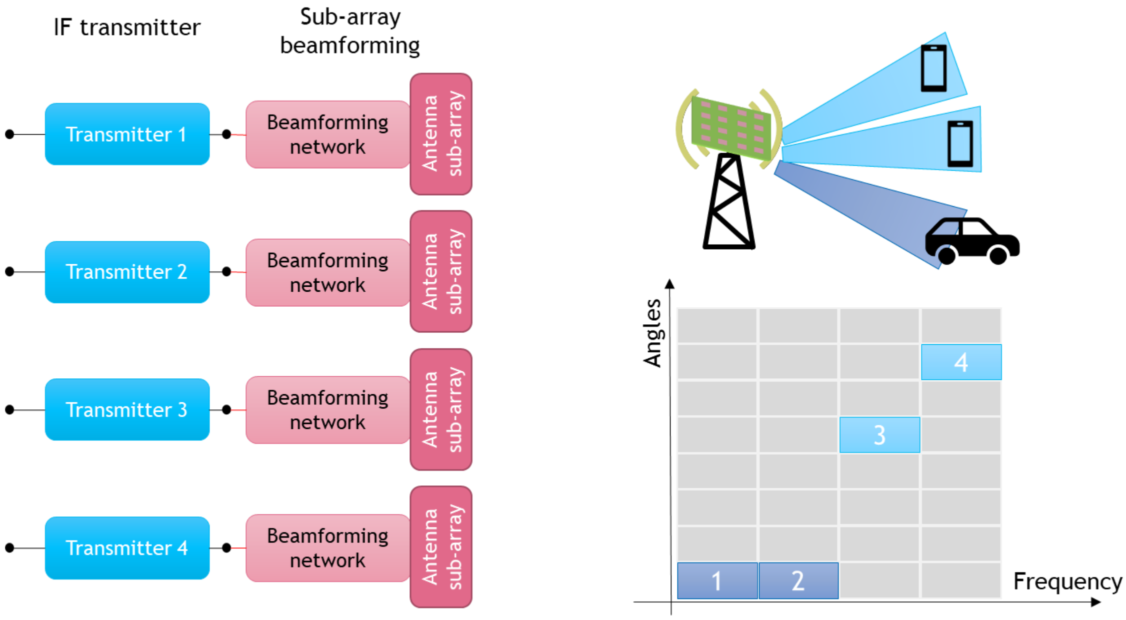

Figure 10-6 Hybrid beamforming configuration with flexible angular-frequency allocation.

10.3Bi-Static joint communication and sensing

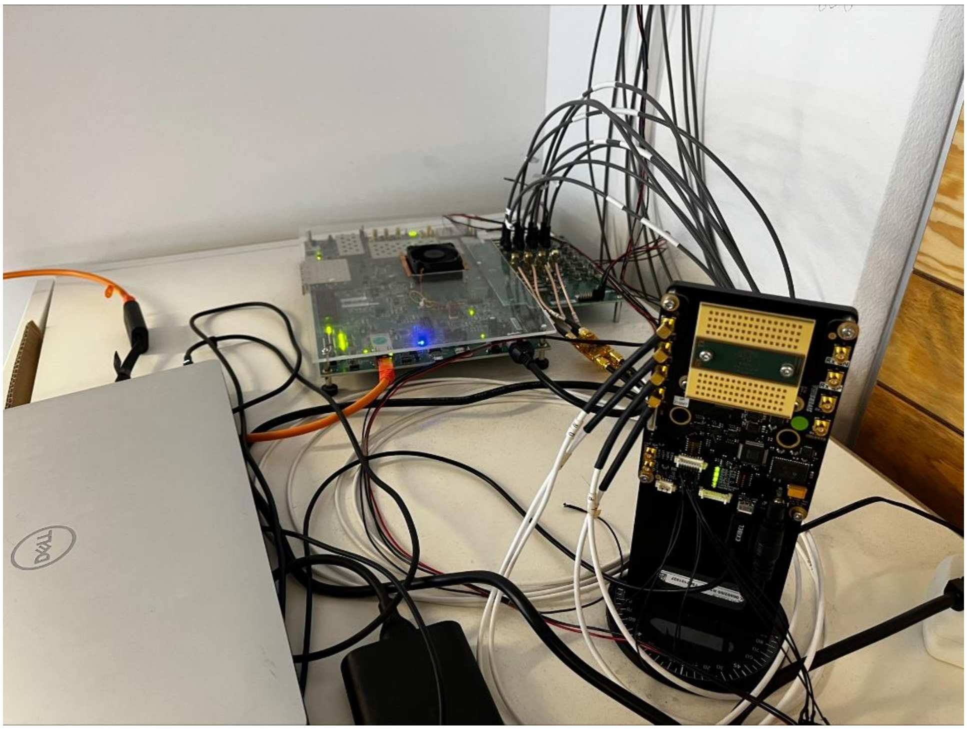

Figure 10-7 JCAS demonstrator

Introduction: The main objective of the demonstrator is to show the possibility of using the same hardware for both communication and sensing. However, it can also be a great tool in the development work, both for evaluating and testing new ideas as well as for other PoCs. It can also be useful for testing performance limits in the presence of hardware impairments.

Description: The joint communication and sensing demonstrator (Figure 10-7) consists of 57-71 GHz radio EVKs for the transmitter and receiver, an RFSoC board for signal processing and a PC for controlling the setup. Supported waveforms are CP-OFDM and DFT-S-OFDM based on the 5G NR standard, but others may be added if needed. The setup can be configured to run in a bi-static or multi-static mode with either 2Tx-1Rx or 1Tx-2Rx.

Measurement setup and experiment scenario: Figure 10-8 illustrates the measurement setup. For the experiment scenario, a waveform based on 5G standard will be developed and used for both communication and sensing. The waveform is stored in the FPGA board (RFSoC). During the experiment, first, the LoS is determined in the initial beam steering by finding the maximum power received from all beam combinations between TX and RX where then the communication will be done according to the corresponding beam pair. Then, the beam steering is maintained continuously for bi-static sensing between the TX and RX. During the process, the received communication waveform and the raw data for target positions are downloaded via ethernet link from RFSoC to the PC and after post-processing will be illustrated via a GUI in the PC.

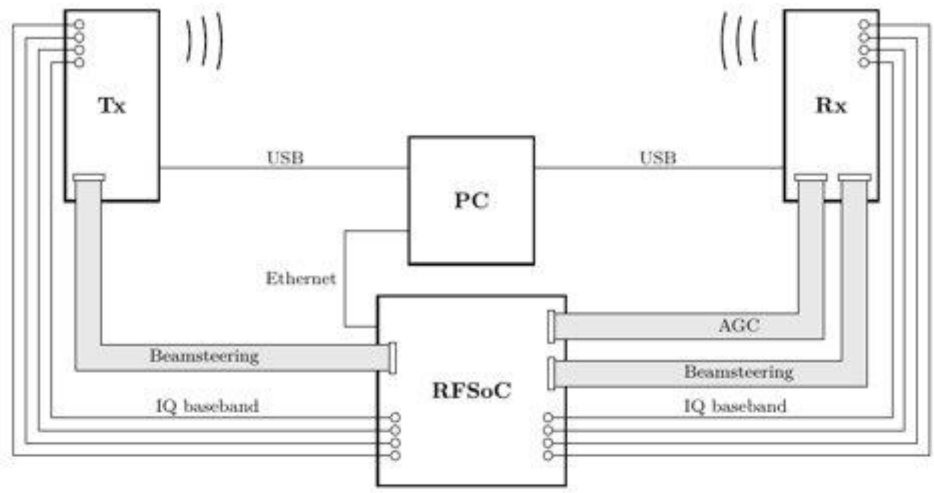

Figure 10-8 Block diagram for the measurement setup and experiment scenario.

Use cases: The demonstrator may be relevant for many use cases which involve JCAS, e. g. digital twins for manufacturing, immersive smart cities, fully merged cyber-physical world and, interacting and cooperative mobile robots.

KPIs/KVIs: The KPIs will be the EVM for communication and the positioning accuracy for the sensing. The goal is to achieve cm precision.

Benchmark: The results should be compared to existing available communication and sensing systems.

Assumptions: Only the physical layer is considered and there is only one-way communication, i.e., no Tx-Rx duplexing.

10.4 Channel measurement data and model

The standardised stochastic channel model 3GPP is considered in the demonstrator. Since this channel model is reported to operate only up to 100 GHz, it is required to collect as much channel data above 100 GHz, along with their lower-frequency counterparts at the same environment, and check whether the existing channel model framework and parameter values agree well enough with that of the measured channels. Various channel parameters such as the large scale, small-scale, cross-correlation, and scaling parameters from double-directional multipath estimates [DHK23] in the entrance hall and outdoor residential environments at 142 GHz have already been derived. They are tested as inputs to the 3GPP channel model presently implemented in MATLAB, without or with modifications, to generate beamspace MIMO channels at 142 GHz. The modifications are for varying levels of details, i.e., 1) custom channel model parameter values derived from our channel sounding, 2) generation of cluster angles, 3) generation of sub-path angles. Beamspace MIMO channel responses reproduced by the 3GPP channel model without an alteration and their variants with minor adjustments in the framework and/or parameter values are compared with those from the developed channel sounding to identify the best possible option of using the existing 3GPP channel model. Agreement of large-scale parameters and eigenvalue statistics of the beamspace MIMO channels is examined to identify the best possible option. Complementary measurements in a corridor, larger indoor spaces, and in factory or workshop type environments at some radio frequencies above 140 GHz and below 320 GHz are planned. New measurements will bring more material for statistical analysis of radio channel and finally for its modelling.

Summary and next steps

This report details technological components and enablers essential for designing 6G radio, spanning a broad spectrum range from sub-6 GHz to THz. Each enabler is discussed in terms of its objective, motivation, scope, functionality, relevant use cases, targeted KPIs/KVIs, and the state-of-the-art benchmark. The report also highlights any assumptions and dependencies related to other components.

The first part of the document introduces the holistic radio design concept, emphasizing sustainability, trustworthiness, and inclusion as foundational values, in addition to the standard performance requirements. From a radio viewpoint, the report outlines performance metrics both for communication and. A relation between the E2E service requirements and the radio requirements is introduced, with an analysis of select use cases. Based on varying KPIs, four radio scenarios emerge, each concentrating on extreme requirements in one parameter, while treating other parameters as flexible. These scenarios are denoted as (1) Extreme coverage, (2) Extreme data rate, (3) Extreme connection density, (4) Extreme low latency and high reliability. These scenarios cater to various use cases. Each scenario specifies key parameters (environment type, deployment option, radio device, mobility, and frequency range). These parameters are then linked to specific values, influencing the radio design hardware architecture and transmission schemes. By selecting concrete parameters, more refined sub-scenarios can be established, leading to an optimized radio design. One or more scenario can be encountered in a single use case, which indicate the need of flexible radio design.

The second part provide a comprehensive list of enablers spanning different aspect of radio design. These can be grouped into six principal categories

1. Architecture and deployment enablers: this focus of category is on radio architectural and deployment solutions. It covers areas of flexible radio hardware architecture, massive MIMO, D-MIMO, RIS-assisted transmission, and JCAS architectures. Taking the propagation environment into account, these enablers have a direct impact on the wireless channel.
2. Radio link modelling enablers: introduces enabling techniques for channel and link-level modelling, considering the wireless channel and hardware impact. Such modelling is essential for the evaluation of transmission schemes and refining signal processing algorithms.
3. Signal processing and algorithms enablers: this category encompasses wide range of enabling for the communication function. It includes waveforms and modulations, (particularly for sub-THz), intelligent transmitter and/or receiver design, especially for enhancing of the communication in FR1, and FR2. Moreover, it involves enablers for JCAS function, such as JCAS waveforms and frame structures. Furthermore, resource allocation enablers are presented, especially for sharing resources among the communication and sensing functions.
4. Flexible spectrum access solutions: this group focuses on spectrum sharing and coexistence of diverse technologies, in addition to enablers for low-latency random access, especially for sub-THz.
5. KVIs-focused solutions: the enablers of this category aim at enhancing KVIs, exploring inclusive radio interface, such as TN/NTN integration, sustainable radio solutions for energy efficiency optimization and EMF assessment, as well as enablers for trustworthiness for security and resilience, highlighting the role of JCAS security and privacy.

The last chapter presents several PoCs and measurement setup, which aim at evaluating enablers with realistic HW and environment. These include, “AI-native air interface” for evaluating intelligent transceiver approaches, “flexible modulation and transceiver design”, to show the concept of flexible HW/SW transceiver architecture, and enable evaluating different signal processing and radio architecture enablers. “Integrated monostatic and bistatic sensing” PoC aims at demonstrating aspects of JCAS, such as reusing the same HW for communication and sensing functions, sharing the spectrum and waveforms. “Channel measurement” will gather measurement and providing models for new frequency ranges, such as sub-THz, and cmWave.

The future work will further on analyse the enablers and provide evaluation results, considering selected radio scenarios. The results will be reported in D4.3 “Early results of 6G Radio Key Enablers”, by April 2030.

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