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Authors:	Kilian Roth (INT), Nicola Michailow (SAG), Aarno Pärssinen (OUL), Hardy Halbauer (NOG), Katsuyuki Haneda (AAU), Tommy Svensson (CHA), Muris Sarajlic (EAB), Yinggang Li (EAB), Leonardo Gomes Baltar (INT), Marko E Leinonen (OUL), Pekka Kyösti (OUL), Antti Tölli (OUL), Andreas Wolfgang (QRT), Xinxin Yang (QRT), Davide Sorbara (TIM), Ahmad Nimr (TUD), Meik Dörpinghaus (TUD), Roberto Bomfin (TUD), Stephan Zeitz (TUD), Yaning Zou (TUD)
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Abstract

This report provides the initial technology assessment of Hexa-X work package 2: “Novel radio access technologies towards 6G”. Out of the use cases developed in Hexa-X, all related to tera bits per second (Tbps) communication are identified. They are further developed into initial requirements related to the physical layer. Based on this requirement gaps of current and future technology are identified. Potential solution of these gaps and the future developments in this work package are also presented.

Keywords

6G vision, physical layer, 100 – 300 GHz, hardware models, beamforming, channel measurements, distributed MIMO

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Executive Summary

The main target of this deliverable is to give a first insight into the current state of the technology (including related deficiencies) for wireless communication in the frequency range of 100 to 300 GHz as well as other physical layer enabling technologies for future wireless communication systems.

We combine a top down approach originating from the use cases with the bottom up approach starting from predicted performance of future systems. These two approaches meet midway to identify promising directions of future work.

The top-down approach relates the use cases developed in Work Package 1 (WP1) of Hexa-X to physical layer and hardware implementation related Key Performance Indicators (KPIs). These KPIs are compared to the related performance achieved by present-day mobile communication systems. Among the use cases related to physical layer aspects the following groups of use-cases are formed:

- Short range wireless connectivity consisting of wireless access and local networks including device to device communication
- Long range wireless connectivity comprising of fixed and mobile wireless links
- Sensing with radio waves connected to localization, mapping and tracking, and spectroscopy

For these use cases technical enablers are derived. Out of these technical enablers only the ones which cannot be addressed by an evolution of current mobile systems, i.e., radio enabling technologies for operating up to 300 GHz (especially in the 100 – 300 GHz range), will be investigated in detail in WP2.

The bottom up approach consists of a gap analysis of the current available technology related to potential future performance requirements. The radio front-end hardware implementation was identified to be a major, additional challenge relative to current mobile communication systems operating at lower frequencies. Physical layer performance requirements are afterwards related to aspects like bandwidth and channelization, mobility, link level performance, range, power consumption, and time domain aspects. In order to assess the gaps of current radio front-end hardware, the state of the art of the following implementation aspects is reviewed: transmit power, receiver noise, phase noise, data converters, digital signal processing, and antenna and transceiver approaches.

Waveform related KPIs and their relation to the radio front-end hardware performance are also described. Waveform candidates including their respective advantages and disadvantages are presented. The impact of the radio front-end hardware and system interfacing decisions on multi-antenna processing in the form of beamforming at higher frequencies and distributed MIMO at lower frequencies are identified by their relation to physical layer performance requirements. As the radio propagation environment at frequencies in the range of 100 – 300 GHz is currently not well understood, shortcomings of current channel models as well as required measurements are described.

This deliverable concludes with a summary of the presented aspects. Details of future work related to all aspects of the bottom up approach are also described.

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List of Acronyms and Abbreviations

Term	Description
EC	European Commission
SotA	State of the Art
UAV	Unmanned Aerial Vehicle
3D	3 Dimensional
3GPP	3rd Generation Partnership Project
5G	5th Generation mobile communication
5G	5G Systems
5G-PPP	5G Public Private Partnership
6D	6 Dimensional
6G	6th Generation mobile communication
A/D	Analogue to Digital
ADC	Analogue to Digital Converter
AFC	Automatic Frequency Control
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AiP	Antenna in Package
AP	Access Point
AR	Augmented Reality
AWGN	Additive White Gaussian Noise
B5G	Beyond 5G
BB	BaseBand
BCJR	Bahl-Cocke-Jelinek-Raviv
BER	Bit Error Rate
BiCMOS	Bipolar CMOS
BLER	BLock Error Rate
bps	bit per second (bit/s)
BPSK	Binary Phase Shift Keying
BS	BaseStation
BT	Bluetooth
BW	BandWidth
CB	Coordinated Beamforming
CC	Component Carrier
CCI	Co-Channel Interference
ceCPM	constrained envelope CPM
CMOS	Complementary Metal Oxide Semiconductor
CPM	Constant Phase Modulation

CP-OFDM	Cyclic Prefix OFDM
CPU	Central Processing Unit
CSI	Channel State Information
C-V2X	Cellular Vehicle to everything
CWDM	Coarse Wavelength Division Multiplex
D2D	Device to Device
D2I	Device to Infrastructure
DAC	Digital to Analogue Converter
DFE	Decision Feedback Equalization
DFT	Discrete Fourier Transformation
DFTS-OFDM	DFT Spread OFDM
DL	DownLink
D-MIMO	Distributed MIMO
DOCSIS	Data Over Cable Service Interface Specification
DPS	Dynamic Point Selection
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplex
E2E	End to End
EE	Energy Efficiency
EIRP	Effective Isotropic Radiated Power
EM	ElectroMagnetic
ENOB	Effective Number Of Bits
EU	European Union
EVM	Error Vector Magnitude
eWLB	embedded Wafer Level Ball Grid Array
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FE	Front-End
FER	Frame Error Rate
FMCW	Frequency-Modulated Continuous Wave
FOM	Figure Of Merit
FSOC	Free Space Optical Communication
FTN	Faster Than Nyquist
FWA	Fixed Wireless Access
GaAs	Gallium Arsenide
GALILEO	Europen Global Satellite Navigation System
GaN	Gallium Nitride
GNSS	Global Navigation Satellite System
GPS	Global Positioning System

H2020	Horizon 2020
HAP	High Altitude Platform
HARQ	Hybrid Automatic Repeat reQuest
HDMI	High-Definition Multimedia Interface
HW	HardWare
I/Q	Inphase/Quadrature
IAB	Integrated Access and Backhaul
IBFD	In-Band Full Duplex
IC	Integrated Circuit
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ICT	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
I-FDMA	Interleaved FDMA
III-V	Compound semiconductor combining elements of group three and five
IIoT	Industrial Internet of Things
IL	Insertion Loss
InP	Indium Phosphide
IoT	Internet of Things
IR	InfraRed
ISP	Internet Service Provider
JT-CoMP	Joint Transmission Coordinated Multi-Point
KPI	Key Performance Indicator
KVI	Key Value Indicator
LAN	Local Area Network
LD	Laser Diode
LED	Light Emitting Diode
LEO	Low Earth Orbit
LiDAR	Light Detection And Ranging
LiFi	Light Fidelity
LNA	Low Noise Amplifier
LO	Local Oscillator
LOS	Line Of Sight
LTE	Long Term Evolution
LTE-A	LTE-Advanced
M2M	Machine to Machine
MAC	Medium Access Control
MF	Matched Filter
MIMO	Multiple Input Multiple Output

MMSE	Minimum Mean Square Error
mmW	Millimetre-wave
NF	Noise Figure
NFC	Near Field Communication
NIR	Near InfraRed
NLOS	Non Line Of Sight
NR	New Radio
NR FR1	NR Frequency Range 1
NR FR2	NR Frequency Range 2
NTN	Non Terrestrial Network
OBO	Output power BackOff
OCC	Optical Camera Communication
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OOB	Out Of Band
OOK	On Off Keying
OSI	Open Systems Interconnection
OWC	Optical Wireless Communication
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PCB	Printer Circuit Board
PER	Packet Error Rate
pHEMT	Pseudomorphic High Electron Mobility Transistor
PHY	PHYsical layer
PLL	Phase Locked Loop
PoC	Proof of Concept
ProSe	Proximity- based Services
PtP	Point to Point
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quaternary Shift Keying
RADAR	RAdio Detection And Ranging
RAN	Radio Access Network
RCS	Radar Cross Section
Rel.	Release
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuit
RIS	Reconfigurable Intelligent Surfaces
RLL	Run Length Limited

RMS	Root Mean Square
RSSD	Reduced State Sequence Detection
RSSI	Received Signal Strength Indicator
Rx	Receiver
SC-FDE	Single Carrier Frequency Domain Equalization
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDMA	Spatial Domain Multiple Access
SiGe	Silicium Germanium
SINR	Signal to Interference and Noise Ratio
SISO	Single Input Single Output
SLAM	Simultaneous Localization And Mapping
SNDR	Signal to Noise and Distortion Ratio
SNR	Signal to Noise Ratio
T/R	Transmit / Receive
TDD	Time Division Duplex
TV	Tele Vision
Tx	Transmitter
UE	User Equipment
UL	UpLink
USB	Universal Serial Bus
UV	Ultra Violet
UWB	Ultra Wide Band
UWB-RTLS	Ultra Wide Band - Real Time Locating System
V2V	Vehicle to Vehicle
VCO	Voltage Controlled Oscillator
VL	Visible Light
VLC	Visible Light Communication
VR	Virtual Reality
w.r.t	with respect to
WDM	Wavelength Division Multiplex
Wi-Fi	Wireless Fidelity
WLAN	Wireless LAN
WP	Work Package
WRC	World Radiocommunication Conference
XR	eXtended Reality
ZF	Zero Forcing
ZXM	Zero-crossing Modulation

1 Introduction

Hexa-X is one of the 5G-PPP projects under the EU Horizon 2020 framework. It is a flagship project that develops a Beyond 5G (B5G)/6G vision and an intelligent fabric of technology enablers connecting human, physical and digital worlds.

This document is the first deliverable of Work Package 2 (WP2) - "Novel radio access technologies towards 6G". The work in WP2 focuses on physical layer and Radio Frequency (RF) implementation aspects for future mobile communication systems. The research focuses on the following key aspects:

- Radio enablers and technology roadmap
- Radio and antenna implementation aspects, hardware component models and architecture
- Hardware-aware waveform and modulation design
- Hardware-aware beamforming design
- Distributed large MIMO systems for beyond 5G/6G
- Channel measurement and modelling for beyond 100 GHz

1.1 Objective of the Document

The main target of this deliverable is to give a first insight into the current state of the technology (including related deficiencies) for wireless communication in the frequency range of 100 to 300 GHz as well as other physical layer enabling technologies for future wireless communication systems.

This report provides an initial assessment of how the use cases developed in D1.2 [HEX21-D12] relate to 6G radio physical layer requirements in general as well as to, within the scope of WP2, study limitations of current and future physical layer and RF implementation for operating up to 300 GHz (especially in the 100 – 300 GHz range). For guiding the work of WP2, we will combine a top down approach originating from the use cases with the bottom up approach starting from predicted performance of future systems. The two approaches meet midway to identify promising directions of future work.

1.2 Structure of the Document

The first part in Chapter 2 is a top-down approach relating the use cases to Key Performance Indicators (KPIs). These KPIs are then compared to the related performance achieved by present-day mobile communication systems. Based on this comparison missing technology aspects as well as performance gaps are identified. We focus on aspects related to short-range and long-range connectivity as well as radio-based sensing. Use cases and KPIs/Key Value Indicators (KVIs) are analysed from a WP2 perspective and with a focus on technical enablers in this document, based on their initial definition and refinement in D1.1 [HEX21-D11] and D1.2 [HEX21-D12]. For KVIs, value entails intangible yet important human and societal needs such as growth, sustainability, trustworthiness, and inclusion. As part of the ongoing work within Hexa-X, harmonization and alignment of initial use cases and KPIs/KVIs of D1.1 and D1.2 with findings from technical work packages will be performed in WP1 and the outcome will be available in D1.3, due in February 2022.

The second aspect in Chapter 3 of this work consists of a bottom-up approach evaluating critical building blocks of the system based on current and envisioned future implementations. The main purpose is to identify critical gaps and limitations of physical layer and HardWare (HW) implementation. We focused on hardware implementation, waveform, beamforming, distributed MIMO, and channel model.

The document concludes with the description of the planned next steps in Chapter 4.

1.3 Definition of Terms Related to Frequency Bands

The research community in the field of wireless communication uses a lot of different terms to define frequency bands. These definitions are either not stable over time or are defined differently using the same name. The following three examples illustrate this problem.

The first example is the frequency range definitions FR1 and FR2 for 3GPP NR. In [38.101-1a] NR FR1 is defined as the frequency range of 450 MHz – 6000 MHz. But as the work in 3GPP progressed this definition changed to 410 MHz – 7125 MHz per the last version of the specification available during the writing of this document [38.101-1b]. The same will likely hold true for FR2 where an extension of the current range 24250 MHz – 52600 MHz is still under discussion.

The second examples are letter descriptions of bands. The definition of the D band can follow the definition based on the waveguide size (WR7 or WG29) which would be the frequency band 110 – 170 GHz. However, there is also another definition of the D band as the frequency range from 1 to 2 GHz by the NATO. The work in [RG20] defines the D band as the frequency range 130 – 175 GHz. In contrast to this definition the work in [FRL19] defines the D band to include the frequency range 130 – 170 GHz.

The term sub-THz is often found in academic literature in the field of future, mobile communication [TLP20]. However, a strict interpretation of this definition would lead to all frequencies below 300 GHz without a lower bound.

We seek to define a clear reference for the frequency ranges in context of Hexa-X and WP2. We plan to adopt the terminology defined in Table 1-1. We also encourage everyone to define the targeted frequency range in terms of the physical properties wavelength for propagation in vacuum or frequency for propagation in vacuum.

Table 1-1: Definition of frequency bands in context of Hexa-X WP2.

Term	Frequency band
mmW	30 – 300 GHz
lower mmW	30 – 100 GHz
upper mmW	100 – 300 GHz
THz	300 GHz – 3 THz

2 Use Cases

The frequency range above 100 GHz holds the potential for channels with large aggregated bandwidth[2]. For communication systems, large bandwidths carry the promise of increased data rates, higher traffic capacity and connection density, as well as finer frequency and time resolution for environment sensing and potentially a lower latency. Shorter wavelengths bring altered properties for the interaction of radio waves with the matter in our environment and make trade-offs between smaller form-factor steerable antenna arrays and link budget possible. This brings also great opportunities for capturing the (physical) environment with radio waves, which for 6G is no longer a by-product but a design target. High resolution of multipath signal components and fine grained beamforming are the foundation for better localization, mapping and tracking of devices and objects. And covering a large range of frequencies with a radio brings us closer to be able to explore the physical properties of our environment with spectroscopy. Further details on opportunities and challenges related to wireless communications and sensing above 100 GHz can be found in [RXK+19], [RAB+20] and [BBL+20].

Of course, most use cases envisioned for 6G (Figure 2-1) benefit from the best data rate and latency with the most compact antenna size possible. However, when approaching the upper mmW frequencies, these properties come with challenges, e.g., limited link range, additional challenges in Non Line Of Sight (NLOS) scenarios, dependency on atmospheric conditions, energy efficiency and potentially high cost of manufacturing, which, until addressed by researchers and engineers, might be prohibitive for some of the envisioned applications. For instance, in addition to challenges in antenna and hardware design, highly directional beams will be necessary to counteract propagation loss, and clever methods to discover and exploit communication paths in NLOS conditions are needed [RRE14, AK16, MSW20].

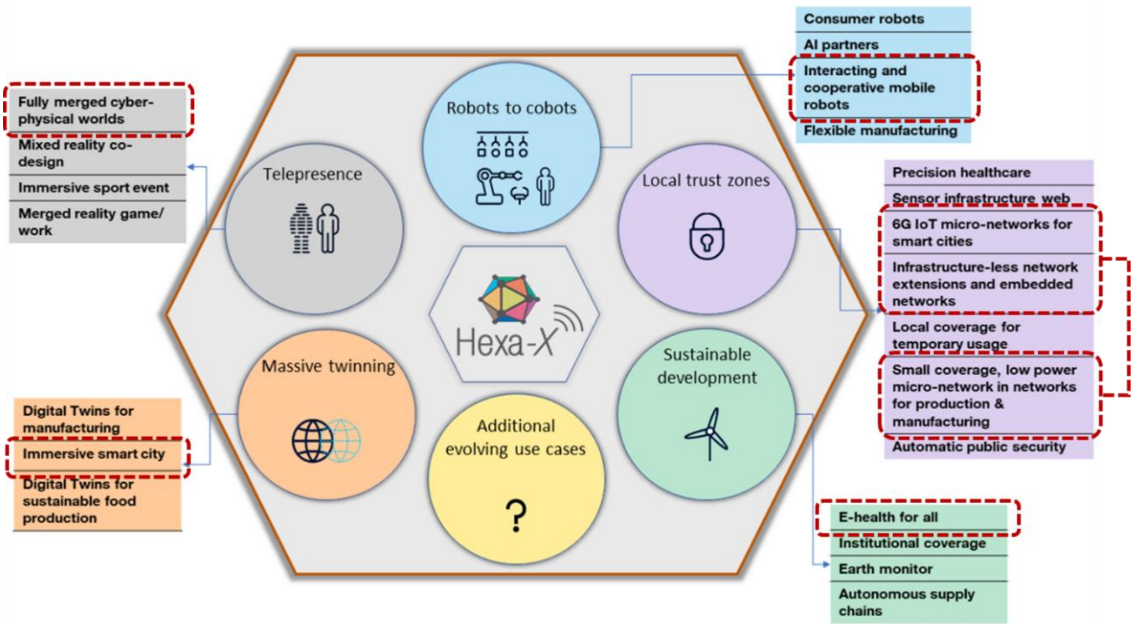


Figure 2-1: Hexa-X use case areas and use cases (from [HEX21-D12]). The highlighted use cases are deemed a "representative subset" in Sec. 6 of D1.2.

[2] Although most frequencies above 100 GHz are occupied (cf. Sec. 7 in D1.2 [HEX21-D12]), it is expected that changes in regulation policies will be negotiated at future World Radiocommunication Conference (WRC). At these frequencies, local (re-)use will play an important role. As of today, aggregated BW up to 10 GHz seems feasible. Spectrum aspects will be further studied in Task 1.5 of WP 1 in Hexa-X.

6G communication systems improving capabilities in the lower mmW frequencies and approaching the upper mmW frequencies will contribute in various ways to the evolution of existing cellular networks (w.r.t. to performance) and also pave the way for establishing new capabilities. Based on the Hexa-X vision, values and use cases, WP1 has identified key challenges w.r.t. KPIs, KVIs and new capabilities [HEX21-D12]. Figure 2-2 highlights the areas where WP2 solutions are expected to contribute to the extreme evolution of established capabilities or to act as an enabler for new ones. The functionality needed from the underlying wireless technology to achieve this can be broadly categorized into “short range wireless connectivity”, “long range wireless connectivity” and “sensing with radio waves”. These three functional areas will serve as an outline for the remainder of this section. Notably, primary focus for our analysis are the existing and new KPIs, as well as, new capabilities. The identified KVI areas will also be supported by the WP2 solutions, although indirectly because of the evolution of technology.

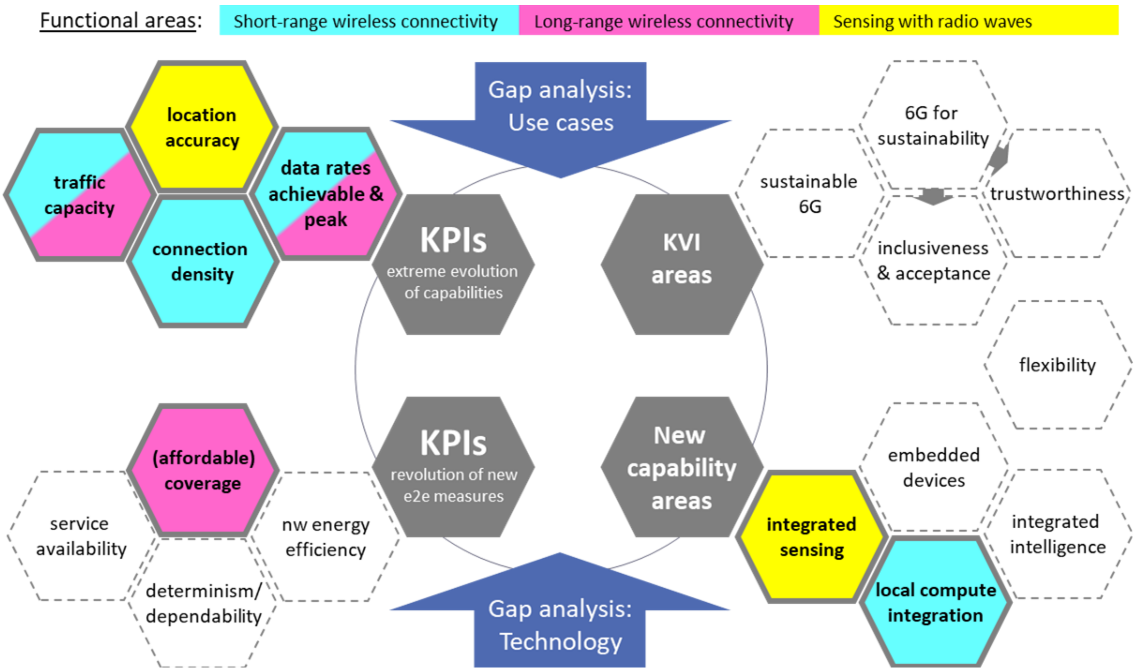


Figure 2-2: Hexa-X KPIs and capabilities footprint, primarily addressed by approaching the upper mmW frequencies, based on Fig. 5-2 from D1.2 [HEX21-D12]. (KVI areas are impacted indirectly.)

Short-range wireless connectivity

In context of this document, we refer to the traditional small-cell scenario with typical cell size below 100 m as short-range wireless connectivity for mmW frequencies (30 – 300 GHz). In contrast to previous generations of cellular systems, emphasis on differentiated optimizations for smaller ranges is expected in 6G. Short-range transceivers capable of operating in the upper mmW frequencies will allow future communications systems to expand into new frequencies. In addition to **data rate**, also traffic and connections per area (i.e., **capacity** and **density**) will generally benefit from access to these new frequencies. Additionally, the increasing signal attenuation at higher frequencies necessitates / gives the opportunity to deploy dense networks of smaller cells. High directivity of the transmissions with narrow beams allows to further optimize the utilization of communication resources. Altogether, these properties will also help with the **integration of local compute** nodes by providing the means to transport data from sensors/displays/actors to the processing and back.

Long-range wireless connectivity

This document treats point to point communication links at distances beyond 100 m as long-range wireless connectivity for mmW frequencies (30 – 300 GHz). Traditional applications include directional radio links across a few kilometres, while emerging scenarios might necessitate link distances of up to 1000 km. In general, more available bandwidth for wireless x-haul (fixed/integrated) will increase achievable and peak **data rates** and **capacity.** Additionally, the mmW frequencies are expected to play an increasing role for wireless backhaul links from and between moving entities like satellites, high-altitude platforms, or swarm-networks, which will be integral for extending the global reach of cellular networks (**coverage**).

Sensing with radio waves

With respect to **location accuracy** and **integrated sensing capabilities**, large signal bandwidth leads to better resolution of multipaths. The rapidly steerable antennas with strong directivity, which are necessary at frequencies beyond 100 GHz to overcome path loss, bring the benefit of increasing the spatial resolution for localization purposes. And lastly, decreasing the wavelength changes how radio waves interact with matter in the physical world. This can be exploited for 3D mapping the environment, detecting human gestures and opens the direction of spectroscopy.

2.1 Short-Range Wireless Connectivity

The following two sections focus on requirements regarding short-range wireless connectivity. We concentrate on communication systems with a range up to 100 meters (which is the typical radius of small cells today).

2.1.1 Wireless Access (Device to Infrastructure)

Wireless access refers to the **means for Device to Infrastructure (D2I) communication at short ranges with low mobility**. This functionality is expected to enable the following use cases in future 6G systems:

- "General purpose" needs for wireless access, e.g., through ceiling-mounted hot spots that are deployed primarily indoors in home and throughout corporate, <u>smart city</u> and industrial campus scenarios.
- Bidirectional streaming between processing unit(s) and devices with display(s)/projector(s)/camera(s), e.g., in mixed reality, <u>telepresence</u>, <u>collaborative remote work</u> and entertainment, requiring fast and symmetrical interaction.
- <u>Digital twin and industrial control</u> applications can benefit from highly directed connectivity and sensing, e.g., for indoors fixed wireless access for static or rarely moving machines.

Wideband access systems in the upper mmW frequency range seem feasible, although as of today these frequencies are mainly known for backhaul rather than access. The following considerations are made with our current experience with frequencies in the range of 110 – 170 GHz in mind.

For the "general purpose" case, the maximum possible data rate feasible within available channel bandwidth with a moderate number of simultaneous users can be made with the following assumptions: a spectral efficiency of 3 b/s/Hz [RAB+20], and 10 – 20 GHz bandwidth and 2 MIMO streams leads to about 60 – 120 Gbps cell rate. Spatial multiplexing with up to 4 streams is considered feasible [HW21]. Latency and reliability are not considered critical as performance is on a par with 5G capabilities, which is sufficient. A range of several tens of meters is seen as realistic. Notably, the cell size should match the intended purpose and the deployment of many radio heads with small coverage area could be beneficial to connect more devices under certain conditions.

The requirements for mixed reality, telepresence, and collaborative remote work differ ([Mic21], [Mic16]): The range between device and infrastructure is smaller, reliability for collaborative work needs to be improved, although extreme values are not required. For human operators, system-level latency requirements are dictated by the limits of cyber sickness, which depend on the involved senses, i.e., audio 100 ms, vision 10 ms, haptic 1 ms. For head-mounted devices, complexity and form factor will be a crucial aspect. AR/VR applications today consume data rates in the order of tens of Mbps, e.g., for streaming 360° video [Qal18]. Notably, there is no adequate consumer solution for streaming 4K/60FPS video to a TV, projector or XR headset as of today, but work on it started in 3GPP by considering the use cases described in [26.928]. At the same time, modern gaming monitors easily reach three times those refresh rates at extra wide screen resolutions, which leads to uncompressed video bit rates beyond 20 Gbps per display. Predictions for holographic communications expect data rate requirements two orders of magnitude beyond that [TSM+21].

For digital twin and industrial control applications, range requirements like the "general purpose" case are expected, e.g., to provide coverage for a room, workshop, or warehouse. For digital twins, high data rates and low latency requirements are expected depending on the properties of the sensors and actors that are deployed. For other control applications the focus is on reliability and low latency with a reduced requirement on the data rate. An envisioned data rate intensive application with up to several hundreds of Gbps is the "data shower" for downloading firmware to a manufactured product, as commonly necessary in the automotive industry.

Due to the short range and indoor nature of these use cases, the target mobility is kept low. Lastly, systems operating in the upper mmW frequencies primarily aim at achieving higher data rates while respecting constrains on the energy efficiency. At this point in time the optimal system architecture achieving this constraint is not known and one target of this investigation is to show alternative solutions to solve the different communication requirements.

Table 2-1: Relevant KPIs and capabilities for short-range wireless access.

KPI	Capabilities today	Capabilities expected
Peak user data rate	Theoretical 5G peak rates (400 MHz carrier) [Eri21b]: • 17.5 Gbps downlink • 9.4 Gbps uplink Public 5G deployments (as of today): 0.2 ~ 1 Gbps downlink [Tha21]	Up to 50 Gbps
Experienced latency	1 ~ 10 ms	0.1 ~ 1 ms
Range	Indoor cell: 25 m Small cell: 100 m	Optimization for different situations expected: • Desk: 2 m • Industrial machine, workbench, hospital bed, etc.: 5 m • Room: 25 m • Industrial campus, train station, etc.: 50 m
Device mobility	Stationary: 0 km/h Pedestrian: < 10 km/h [ITUM2410]	Stationary: 0 km/h Pedestrian: < 10 km/h

2.1.2 Local Networks (Device to Device)

Local networks are envisioned to utilize **Device to Device (D2D) communication as means to disseminate information locally and facilitate collaboration among robots, people, and devices**. Universal benefit of networking based on direct D2D communication links is the fact that data circulates (only) locally, which allows to conserve communication resources and/or adds an additional layer of protection to the data privacy of the exchanged information.

In the area of D2D communication, the WP2 solutions are expected to have strong impact for the following use cases:

- In the area of digital immersion and telepresence, data rates necessary for wirelessly connected displays and docking stations need to be provided (similar to what has been described in Section 2.1.1)
- Further adoption of directed point to (multi-)point links will offer new opportunities for managing the finite amount of communication resources. This will facilitate large-scale collaboration among machines (e.g., swarms of AGVs, drones light show) or people (local multiplayer gaming) with many participants.
- For e-health applications (e.g., handling patient data) and more broadly, local trust zones, solutions approaching upper mmW frequencies can contribute with high spatial directivity of the communication and the fact that higher frequency radio waves are even more susceptible to blockage by obstacles and walls, which can be exploited as an additional layer of information security.

Historically, D2D communication was introduced to 3GPP in Rel. 12 (more details can be found in [RS21a]). It is currently being explored in Rel. 17 under the term "ProSe". The "Study on System enhancement for Proximity-based Services in 5GS" [23.752] identifies and evaluates architecture enhancements of 5G needed to support proximity-based services in the public safety areas (e.g., first responders) and commercial use cases (advertising, social networks, gaming, wearables, and C-V2X). This work will be likely enhanced further and extended to further areas in Rel-18.

Looking ahead, requirements for digital immersion in video and gaming can be derived from USB4 specifications [USB21], i.e., wireless data rates beyond 50 Gbps per user with experienced latency below 10 ms are a desirable target. Contemporary D2D solutions (whether ad hoc or infrastructure-based) are IEEE 802.11ad and IEEE 802.11ay in the 60 GHz bands, the former promising 5 – 7 Gbps and 10 m range and the latter claiming to achieve 20+ Gbps and 100+ m range. Notably, existing wireless HDMI solutions (also operating at 60 GHz frequencies) promise 4K/60FPS uncompressed video transmission with a 10 m range having less than 100 ms latency. However, these products are not intended for applications that involve mobility [Pur21], which would be desired in AR/VR scenarios. Also, the latency is approx. 10x too high for gaming and AR/VR. The short range properties of mmW frequencies and the strongly directional communication have additional benefits as one can multiplex many devices, e.g., wireless docking stations, in an open-plan office.

Collaborating machines, e.g., industrial AGVs, usually rely on 2.4 GHz and 5 GHz Wireless LAN solutions, with the adoption of 5G private cellular networks being imminently expected. Drones communicate through several frequencies between 20 MHz and 8 GHz [SRMCC18, Sec21] as of today, with heavy focus on the 2.4 GHz and 5.8 GHz bands. For AGV platoons and drone swarms, enabling potentially large numbers (100+) of D2D link pairs with latencies below 1 ms would increase autonomy and create new opportunities for hierarchical wireless control loops. One challenge here is the reliable multiplexing of many connections in a confined area, which could be addressed through clever utilization of steerable antenna arrays. Another capability gap that needs to be addressed before mmW frequencies can be considered for platoons, swarms and wearables is the limitation of current solutions to cope with mobility of the communicating nodes (cf. fixed wireless access and [Pur21]), i.e., aspects like rapid link adaptation and dynamic handovers in case of obstruction of the Line Of Sight (LOS) path, or how to efficiently manage more than one spatial link per user to achieve resilience to obstructions.

Today, local trust zones in corporate and military environments are created by constructing special conference rooms and high security zones with EM shielding for eavesdropping protection [EMs21]. Similarly, security- & privacy-sensitive wireless indoor application can be realized with optical wireless communication systems (when windows are covered). In this context, as signal attenuation grows as the wavelength shrinks, future local wireless connectivity at operating frequencies above 100 GHz can bring privacy-enhancing properties to new areas like e-health or manufacturing campus, where construction measures may be out of scope.

Notably, restrictions to receiver complexity and energy efficiency may apply when mobile nodes are employed, as these are generally battery operated and may require a small form factor. In combination with the other requirements, this dimension can lead to additional gaps that need to be addressed.

Industrial special-purpose networks and immersive telepresence scenarios will be further investigated in WP7. Lastly, local networks of any kind may need a backhaul connection, which will be addressed in Sec 2.2.

Table 2-2: Relevant KPIs and capabilities for short-range local networks.

KPI	Capabilities today	Capabilities expected
Range	AGV platoon, drone show: 100 m Consumer WLAN: between 100+ m and 10 m (IEEE 802.11ay)	AGV platoon, drone show: 100 m and with more participants Body-area network: Max. 1 m
Experienced latency	Wireless display: 100 ms [Pur21]	Wireless display, gaming: < 10 ms Hierarchical control loops: 0.1 ~ 1 ms
Device mobility	Stationary (0 km/h) [Pur21]	Pedestrian (< 10 km/h) AGV (< 30 km/h) Drone (< 100 km/h)
Energy efficiency and receiver complexity	May be constrained	May be constrained
Data rate	Sensor tags: Hundreds of kbps (NFC) Consumer WLAN: Tens of Gbps (IEEE 802.11ay)	Peak rates beyond 20 Gbps per link and with support for mobility

2.2 Long-Range Wireless Connectivity

Long-range wireless links are expected to provide coverage in underserved areas (typically sparsely populated and/or hardly accessible), which cannot be covered by short-range infrastructure. Additionally, they are deemed a cost-effective option for densification of wireless networks, where connecting access points / radio units via fibre would be otherwise cost-prohibitive. Technologies of interest include fixed Point to Point (PtP) links, Fixed Wireless Access (FWA) and Non Terrestrial Networks (NTN).

2.2.1 Fixed Wireless Long-Range Links

Already today, upper mmW frequencies are used for directional wireless links between stationary nodes **when laying fibre to extend the reach of wireless networks is not convenient**. Making the technology more common and more accessible (also in terms of cost) will be an essential building block that will create opportunities to further extend the reach of present-day cellular networks. Mainly the following use case areas will be enabled:

- In smart city situations, WP2 solutions will support urban densification of communication networks by using wireless interconnection between small cells when traditional cabling is not possible. This will also contribute towards improved coverage and QoS along infrastructure channels like highways and railroads.
- Complementary to the functionality discussed in Sec 2.2.2, extending the reach of future wireless networks by expanding and further improving the deployment and performance of 5G FWA will allow to include more communities with high-grade wireless services and hence contribute to a sustainable development of societies.
- Indirectly, wider adoption of fixed wireless links will create the data pipes necessary for telepresence and cooperating machines. Local networks will benefit through backhaul/uplink connections to the public or private network in which they are located, if necessary.

Common characteristics of fixed wireless links are the point-to-point, bidirectional nature, predominantly in outdoor scenarios (but also indoors between radio heads). Limited or no mobility is expected. Due to the shrinking wavelengths of the involved wireless signals, QoS is increasingly susceptible to loss of LOS due to varying atmospheric conditions (precipitation, clouds/fog, wind [SB02]) or seasonal changes (trees/foliage). Additionally, fixed obstacles like buildings and mountains may impose restrictions when planning the location of fixed wireless links.

Two technologies differing primarily in cost and complexity of implementation can be discerned in the domain of fixed wireless access in the state of the art. One represents fixed point to point links providing backhaul capabilities for infrastructure nodes. Beyond 5G and towards 6G, the development of this technology will continue towards using more bandwidth at frequencies above 100 GHz and MIMO to achieve bitrates greater than 100 Gbps. Achievable ranges are below 2 km distance, with the possibility of extension using multi-band hops (at the expense of capacity). Other important fixed long-range wireless technology is fixed wireless access, employing: a cell-based approach; advanced outdoor fixed receiver equipment with high directivity; and use of sub-6 GHz and 20 – 30 GHz bands for achieving a good tradeoff between coverage and throughput. In practice, measured throughputs in the order of 1 Gbps are reported for systems operating in the range of 20 – 30 GHz [Eri21]. The upcoming generation of products is expected to achieve throughputs up to 10 Gbps through aggregation of sub-6 GHz and mmW frequency bands [Qal21]. Non-terrestrial networks, particularly Low Earth Orbit (LEO) satellite networks will compete with terrestrial FWA for providing fixed wireless access – relevant KPIs and capabilities of NTNs are provided in Section 2.2.2.

Table 2-3: Relevant KPIs and capabilities for fixed wireless long-range links.

KPI	Capabilities today	Capabilities expected
Throughput	Infrastructure backhaul: 100 Gbps [Eri19]	Infrastructure backhaul: Up to 1 Tbps

	Fixed wireless access (lower mmW): 1 Gbps per subscriber [Eri21]	Fixed wireless access (lower mmW): Up to 10 Gbps per subscriber
Range	Infrastructure backhaul: < 2 km [Eri19] Fixed wireless access (lower mmW): 7 km	Infrastructure backhaul: 2 km
Availability	Infrastructure backhaul: 99.995%	Infrastructure backhaul: 99.99 – 99.999%

2.2.2 Mobile Wireless Long-Range Links

Whenever at least one communication node in a point to point link is moving, fibre is ruled out as an option. In such cases, long range wireless links that support mobility will lay the foundation for mobile base stations in 6G communications systems. Big impact for the following areas is expected:

- Sustainable development of societies by making possible remote medical services, digital inclusion, education outside of urban areas.
- Enabler for local networks that form out of reach of land-based infrastructure (e.g., an aircraft, vessel), where the local network might need a connection to other local or global networks.
- Evolving use cases for space-for-earth applications [AK19], and further ahead the road also for space-for-space industry [WS21].

By the end of the last decade, several of the largest tech companies embarked independently on a quest to expand the reach of internet platforms through communication networks with mobile base stations. Two prominent projects were based on High Altitude Platforms (HAP) [Wik1, Fac16]. As of today, these efforts have been terminated, because unprecedented reduction of cost for launching “things” into Earth orbit has opened the path of large scale LEO satellite deployments [Sta21]. Satellite-based communication networks are a very promising candidate to extend coverage of terrestrial communication networks to currently underserved (remote) areas. In 3GPP, the first study on NTN was conducted in Rel. 15, while the first normative work is expected in 2022 [LRU+21].

Primary concern for consumer broadband services are data rates and latency. With respect to satellites, keeping weight and form factor minimal is imperative. Further, although solar panels allow energy self-sufficient operation (which is positive for the ecological balance), energy constraints for communication systems might still apply.

Distance and mobility of the communication nodes poses a challenge, as orbits and inter-satellite distance can be several hundreds of kilometres. The subscribers’ stations on Earth generally need to be stationary and placed outdoors. The signal quality may vary with atmospheric conditions. From a customer perspective, service coverage for mobile subscribers would be highly desirable (bus, train, airplane, ship) and cost of the equipment is also a determinant factor.

As of today, consumers can expect data rates in the order of 100 Mbps and latencies in the order of 20 – 40 ms for satellite-based broadband services, using frequencies up to 30 GHz. In future, approaching the Gigabit range of speed (like modern fibre Internet connections based on DOCSIS 3.1) and scaling up the number of users can easily necessitate 1 Tbps long range wireless links. In addition, if pushing the latency in the order of 10 ms is possible this would make these services of interest for competitive gaming and VR.

Optical communication solutions are also a candidate for communication links across satellites, HAPs, and ground stations [Lan21], [Myn21a], [Myn21b], [NASA20], [SPM+18], [Def21]. However, they are susceptible to line-of-sight blockage by buildings and mountains, as well as, platform rotations and/or vibrations. Additionally, precipitation, clouds/fog and foliage can cause temporary connection problems for Earth-based stations.

Table 2-4: Relevant KPIs and capabilities for mobile wireless long-range links.

KPI	Capabilities today	Capabilities expected
Throughput per user	Starlink: 100 Mbps HughesNet: 25 Mbps	Up to 500 Mbps
Coverage	USA and Canada (Starlink) North and South America (HughesNet)	Global, outdoors (land and sea)
Mobility	Starlink: • Zero mobility at terrestrial station with retail equipment • Aircraft speed at terrestrial station with dedicated equipment. • Currently limited to one satellite cell. HAPs: Aircraft speed	Planet-side station mobility: • Building: 0 km/h • Vessel: 100 km/h • Car/truck: 200 km/h • High speed train: 500 km/h • Aircraft: 1000 km/h
Latency	30 ms	10 ms

2.3 Sensing with Radio Waves

While the functionality described in the following sections do not directly contribute to achieving Tbps data rates, it is rather an area that will greatly benefit from conquering the upper mmW frequencies and as such it receives increasing attention. Note that sensor network topics like power deliver and sensor charging with EM waves are treated in WP7 as part of the envisioned special-purpose functionality for 6G systems.

2.3.1 Localization

Implementing the **means for devices in future 6G systems to obtain accurate information about their location** will make application-layer coordination between autonomous "things" and the location-based interaction between users (humans, machines) and environment possible.

- With respect to massive twinning of the physical world, location information will allow to put data from different sources (e.g., sensor measurements, application data) in relation, i.e., facilitate the creation of digital twins.
- Towards merging the physical and digital worlds in telepresence scenarios, localization functionality will allow to detect participants in the environment and help collecting data and projecting avatars and visual augmentations in AR/VR applications.

- The formation of local networks, e.g., cooperating machines, proximity-based interaction of consumers with the environment, will heavily rely on location information

Additionally, built-in localization functionality will also create new opportunities for optimization in future 6G systems, e.g., enabling (pre-emptive) radio resource management and beamforming.

Over the last 30 years we have become reliant on Global Navigation Satellite Systems (GNSS) in outdoor situations, which have global coverage and in practice provide a positioning accuracy in the order of 5 – 10 m for consumers.

When indoors, Bluetooth (BT) systems based on measurements of the Received Signal Strength Indicator (RSSI) are traditionally used for asset tracking. Bluetooth version 5.1 brought enhancements that additionally allow to determine the direction of the received signal using multiple antennas [Blu51]. Moreover, Ultra Wide Band (UWB) systems using IEEE 802.15.4 standard have absolute position capabilities [IEEE802154]. In factories and warehouses, UWB-based Real Time Locating Systems (RTLS) offer generally better accuracy and latency when compared to BT or NFC solutions. Notably, computer vision (object detection and tracking with a camera) can also be used, either standalone or in combination with other information sources [NKP+20].

The expansion of future 6G systems into higher frequencies will have significant impact on the localization capabilities. The accuracy w.r.t. time measurements and multipath resolution, will be enhanced with large bandwidths beyond 500 MHz, which are available in the upper mmW-region. Moreover, enhanced beamforming capabilities and beam width reduction that follow from the reduced wavelengths will also contribute to higher positioning accuracy. From this arises the challenge to keep the acquisition time low as the number of beams to cover 360 degrees grows.

Compared to existing UWB-based RTLS solutions that require deployment and maintenance of dedicated infrastructure, integration of such functionality into 6G systems will be a primary enabling factor. Besides extreme hardware capabilities and optimized waveforms that will contribute to higher accuracy and faster measurements, localization systems will greatly benefit from dense deployment of infrastructure (radio units). Here, size reduction of the steerable antenna arrays for the higher frequencies can be considered as a trade-off at the expense of reduced SNR. From the perspective of mobile terminals, device cost and battery size will be additional concerns. Since systems operating at mmW frequencies are not particularly energy efficient, algorithms to combine location information obtained hierarchically through multiple frequency bands might be needed to keep the energy per location measurement low.

More information about current development can be found in 3GPP Rel. 17 [38.857]. Further requirements and solutions related to high-resolution localisation (position & orientation), mapping and sensing will be studied in WP3 “6D high-resolution localisation and sensing”.

Table 2-5: Relevant KPIs and capabilities for localization.

KPI	Capabilities today	Capabilities expected
Accuracy for 90% of devices	Requirements 3GPP Rel. 17 for IIoT [38.857]: <0.2m (horizontal), <1m (vertical) Commercial UWB systems: <0.3m 3GPP Rel. 16 based PoC: <0.2m (horizontal & vertical) [Qua21]	Robot navigation: mm accuracy Interact with a door: 0.10 m Other interaction with environment / robots: 0.50 m Smart city: 5 m (cf. [WSL+21])

Mobility	Requirements 3GPP Rel. 17 for IIoT [38.857]: 3 km/h	3 km/h – 600 km/h [WSL+21]
End-to-end latency	Requirements 3GPP Rel. 17 [38.857]: • PHY: 10 ms • End-to-end: < 100 ms	End-to-end: 10 ms
Used bandwidth	UWB: 500 MHz (impulse radio) 3GPP Rel. 16 based PoC: 400 MHz GPS: 10 – 15 MHz (direct sequence spread spectrum) GALILEO: 30 – 50 MHz	> 500 MHz
Energy consumption	UWB systems in practice: • Before 2021: 80 mJ • Since 2021: 27 mJ	20 mJ per measurement
Coverage area	5G categorization: • Indoor: 20m • Urban Micro: 200m • Urban Macro: 500m UWB: • Systems operate with 10-15 m in practice	Up to 200m [WSL+21]

2.3.2 Mapping and Tracking

Active mapping and tracking functionalities employ **radio waves to capture the shape of the environment or objects/people in the environment**. Both cases have in common that the scanning device actively emits a signal, while the scanned subject is passive; this concept is also generally known as radio detection and ranging (radar). Radar sensors today are predominantly used in the automotive, aerospace, and military sectors. The convergence of the communications domain and the radar discipline ([DBB+21], [PGG+20]) is envisioned to enable new environment-aware applications in the following areas:

- Generally, the increase in carrier frequency and bandwidth will allow higher scanning resolutions. In the future, this will make it possible for communication equipment in public and private spaces to build accurate maps of the physical environment, i.e., digital twins, and update them on a continuous basis. Future 6G networks will be able to leverage this information to optimize the communication.
- With particular focus on the tight integration of communication and radar functionality, RF modules for the upper mmW frequencies will support cooperating machines by paving the way for an evolution of today's automotive radars.
- In telepresence, mapping, and tracking capabilities will enable new ways of human-machine interaction through detection of gestures as an alternative to mouse, keyboard, and touchpad. They will allow to create digital replicas of people (avatars) and their surroundings.

- Also impacted are the smart city and e-health areas, which could benefit from presence and gesture detection capabilities in 6G cellular networks.

Considering human-machine-interaction in entertainment, medical and industrial areas, the resulting latency will be a key parameter for the usability. Vision-based applications require it to be less than 10 ms for imperceptible synchronization of actions and reactions, while less than 1 ms is needed when the sense of touch is involved. For presence detection, occupancy analysis and more broadly, building management, scanning range of several tens of meters will be needed and very high scanning resolution is expected. With respect to medical applications like breathing detection or fall detection, it is imperative to avoid false positives/negatives at application level. Altogether, widespread adoption will depend on cost reduction of the technology. Further, a large challenge ahead is the development of domain-specific application-level signal processing algorithms for different applications. In many cases, the exchange of gathered information, e.g., an absolute reference point or an update of learned maps, between users / devices / clients will be integral for value creation.

Mapping and tracking solutions today are often based on radar (e.g., Frequency-Modulated Continuous-Wave (FMCW) radar in automotive [imec21]) or optical methods. Over the past years, tremendous cost reduction for LiDAR sensors has allowed its adoption for AGVs, automotive applications and it even ships with high-end smartphones. Most modern VR systems are equipped with (multiple) cameras and robot vacuums can use either one for Simultaneous Localization or Mapping (SLAM). However, with the optical approach, ambient light and weather conditions can become a challenge when operating outdoors.

An important open question in context of RF-based mapping and tracking sensors that operate in the mmW frequencies, is how to ensure preservation of privacy. Its answer will need to be aligned with the European core values.

Table 2-6: Relevant KPIs and capabilities for mapping and tracking.

KPI	Capabilities today	Capabilities expected
Resolution	OWC (VLC in indoor; OCC in indoor and outdoor; LiDAR in outdoor): cm-level [CHI+18]	cm-level (while re-using 6G devices/infrastructure for mapping & tracking)
Range	LiDAR: 200 m (e.g., Ouster OS2 [Ous21])	200 m (while re-using 6G devices/infrastructure for mapping & tracking)
Speed of scanning	LiDAR: 10 – 400 Hz	Up to 500 Hz

2.3.3 Spectroscopy

Spectroscopy is the study of the frequency dependence of **the interaction between ElectroMagnetic (EM) radiation and matter**, e.g., atoms and molecules. Examples include absorption, emission, scattering and reflection.

Radio frequencies can penetrate certain materials that are opaque to optical inspection. Depending on the wavelength of the used signal, many non-metallic or non-polar materials (textile, paper, plastic, and ceramics) appear transparent to some degree. Hidden or buried materials can thus be identified in structures containing layers, packaging, or clothing. In particular, mmW and Terahertz-based imaging devices allow screening for illegal substances, poisons, explosives, concealed items and with shorter wavelength the image resolution increases.

mmW and Terahertz radiation is non-ionizing, i.e., the energy per photon is not sufficient to break chemical bonds or to ionize atoms or molecules [ICN12]. For frequencies between 10 – 300 GHz, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommends 10 W/m^2 as limit to human exposure to electromagnetic fields (averaged over time: 6 min at 10 GHz, 10 s at 300 GHz). More information on this topic can be found in [ICN20].

Note that the focus of these considerations is how signals with shorter wavelengths, which will be available once the upper mmW frequencies are made accessible for communications, can enable new sensing applications. Open question outside include network structure for such sensing devices, accuracy measures, calibration, and power consumption, which however are outside of the WP2 scope.

Shorter wavelengths can produce higher-resolution. This creates opportunities in e-health:

- Medical Imaging and Diagnostics: Compared to X-rays, mmW and Terahertz medical equipment is non-ionizing and can distinguish biomolecules and tissues directly. This makes it a candidate for enabling early personalised diagnoses of diseases, such as skin cancer or dental caries.
- Pharmaceutical: Terahertz non-destructive testing can monitor critical quality attributes of pharmaceutical products, which helps the pharmaceutical industry to improve the quality of the products, inherently enhancing its competence. Additionally, it can help the pharmaceutical industry to fight against falsified and counterfeit medicines.
- Food and agriculture: detect the use of chemicals and hormones in food and livestock production, detect possible residual pesticide in food, which addresses increasingly important issues in the modern society.

Applications today are limited by the lack of sufficient technologies to effectively bridge the transition region between lower mmW frequencies below 100 GHz and optics above 10 THz, while both these regions are readily accessible via well-developed electronic and laser-based approaches. Further concerns are cost, form factor, detection range and sensing resolution.

6G devices and infrastructure with such sensing are not necessarily expected to cover the frequency range from 0 Hz to 300 GHz continuously. Rather, the question is what information can be obtained from selected “spectral lines”, which coincide with the 4G, 5G and future 6G frequency bands.

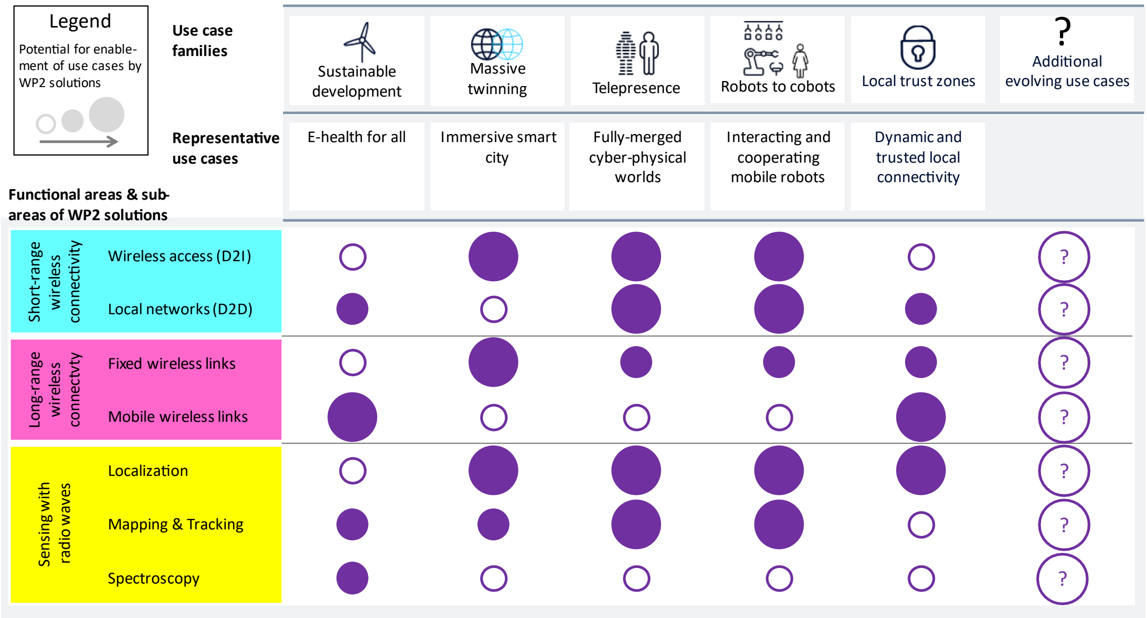
Table 2-7: Relevant KPIs and capabilities for spectroscopy.

KPI	Capabilities today	Capabilities expected
Frequency range	Up to 100 GHz (e.g., airport scanner) [RS21b] Optics (e.g., IR camera) [Qde21]	Up to 300 GHz (as intermediate step towards closing the gap between 100 GHz and 10 THz)
Form factor	Scientific equipment with range up to 5 THz: 0.5 m x 0.5 m x 0.5 m [Ter21] Infrared spectrography: 0.15 m x 0.15 m x 0.15 m [Qde21]	Integration in smartphone Integration in access points
Measurement distance	Airport scanner: Approx. 2 m	Smartphone: 0.1 m Access point: 25 m

2.4 Summary: Key Enabling Properties of WP2 Solutions

The functionality of 6G wireless solutions approaching the upper mmW frequencies has been categorized into "short range wireless connectivity", "long range wireless connectivity" and "sensing with radio waves" and further detailed in Section 2.1 to Section 2.3. Based on the use cases descriptions in D1.2 [HEX21-D12], Table 2-8 gives a summary how these functionalities are expected to contribute to the realization of the envisioned Hexa-X use cases.

Table 2-8: Expected enablement of the representative 6G use cases identified in WP1 by the envisioned WP2 solutions exploiting the mmW frequencies in different functional areas.



The role of WP2 solutions can be summarized as follows:

For e-health:

- Extend the range of future networks
- Facilitate local connections (e.g., for machine learning and other computational tasks)
- Detect gestures for new ways of human-machine interaction
- Conquering the upper mmW frequencies for communication systems will also pave the way for new sensors based on spectroscopy

Immersive smart city:

- Support densification of urban networks through more flexibility for backhaul applications
- Provide high speed local wireless access, e.g., in public spaces/buildings
- Provide location information and presence detection, which are crucial for building digital replicas / digital twins

For fully merged cyber-physical worlds:

- Pave the way for gestures as a new way for human-machine interaction
- Increase localization accuracy to support digital (re-)creation of the physical environment
- Enable short range bidirectional streaming of video data with unprecedented resolution and refresh rates for AR/VR applications

For interacting and cooperative mobile robots:

- Unlock indoor localization as a key functionality for interacting machines in industrial environments, and boost its accuracy
- Provide means for densification of indoor networks through smaller cells and wireless x-haul, and through this support a potentially large number of devices in a confined area
- Allow to keep communication patterns and computation close to the application to conserve communication resources

For dynamic and trusted local connectivity:

- Provide enhanced localization for local networks that are on the move (vehicle platoons)
- Enable dynamic wireless backhaul for local networks that need a communication link to connect to other network(s)

For additional evolving use cases:

- Enable innovation w.r.t. use cases through enablement of functionalities that are new compared to the previous generations of cellular networks: the concept of local networks, wireless x-haul that supports mobility, accurate (indoor) localization and new sensing capabilities of the radio interface

It is important to mention that the realization of all the above-mentioned use cases will require the development of diverse radio enabling technologies for 6G stemming from a simple evolution of current mobile system or from a more drastic or even disruptive change. In WP2, we will only investigate the ones which cannot be realized by a simple evolution of available wireless communication systems. In particular, we mainly concentrate on the use cases requiring high data rates far beyond the capabilities of present-day systems for wireless access as described in Section 2.1.1. In the view of Hexa-X, the required technology for the use cases in Sections 2.1.2 to 2.2.2 can be developed based on existing physical layer technology of current communications standards available in 3GPP and IEEE. For the sensing use cases on localization and mapping and tracking in Sections 2.3.1 and 2.3.2 we expect that some of the required technology will be developed in WP3 of Hexa-X. So far, the only use case without a clear path towards an investigation of the feasibility in either Hexa-X internal or external development is spectroscopy describe in Section 2.3.3. It is possible that this gap will be filled by future projects or other research activities.

2.5 Technical Enablers for Use Cases

2.5.1 WP2 Methodology

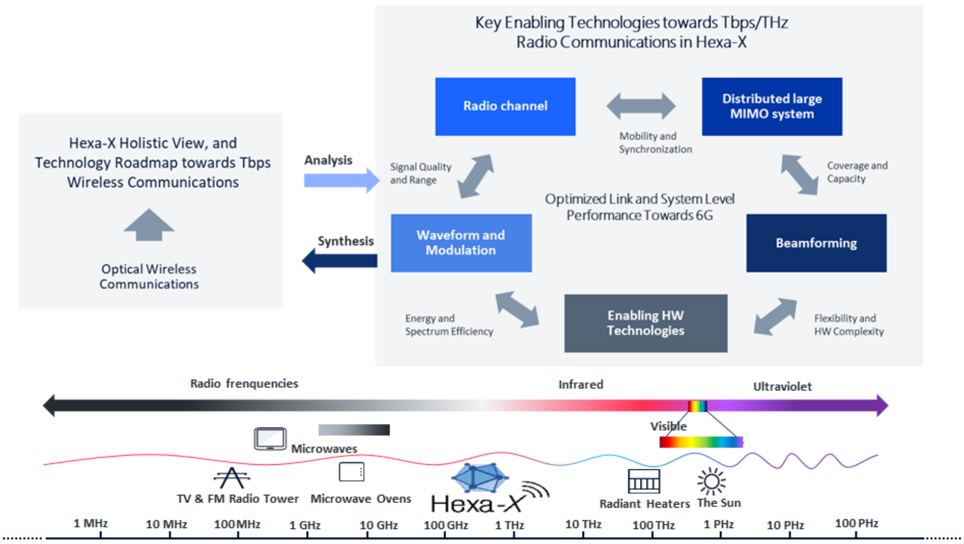


Figure 2-3: WP2 methodology in relation to the overall Hexa-X methodology.

To address the identified use cases and KPI requirements, the technical work in WP2 will focus on jointly developing radio enabling technologies up to 300 GHz range where current semiconductor technologies can potentially provide commercially viable HW solutions. In addition, during the whole project duration, WP2 will also look at a horizon of the next 10 years towards 6G and extrapolate results on network and HW design as well as channel modelling to above 1 THz. Together with integration of current Optical Wireless Communications (OWC) at a conceptual level, WP2 will also synthesize all the design aspects into a forward-looking technology roadmap that provides insights and predictions for the evolution of communications systems towards Tbps link and capacity in the next 10 years as depicted in Figure 2-3 towards the end of the project.

2.5.2 Key Enabling Radio Technologies

During M5 – M27 of project running time, WP2 will carry out joint and in-depth study on five key enabling radio technologies including

- Characterization of radio channel at upper mmW range
- RF architecture and HW modelling for system study
- Waveform and modulation taking energy efficiency-spectrum efficiency-implementation complexity trade-off into account
- Hardware-aware beamforming
- Distributed large MIMO systems.

As the first step, based on the identified use cases in the Sections 2.1 to 2.3, WP2 performed technological gap analysis for each of above key enabling radio technologies. The gap results will be reported in detail in Section 3 and will guide the extensive technical work conducted in WP2 in the following 21 months.

WP2 will work closely with WP3 on developing key enabling radio technologies, fostering the synergy between communications, and sensing in future 6G systems. A joint WP2 WP3 demo will be developed towards the end of project, verifying selected 6G candidate waveforms, and evaluating their performance in real-world deployment scenarios for both communications and sensing.

2.5.3 Integration of Optical Wireless Communication

OWC technologies are seen as an alternative approach to RF spectrum technologies in the evolutionary path of wireless systems and are envisaged in light of their integration in the flexible network of networks from the architecture’s viewpoint under WP5 remit, as a component of the solution for Tbps wireless communications for the next 10 years towards 6G. It is of high importance to recognize this optical aspect in WP2, while striving for a holistic view, and technology roadmap towards Tbps wireless communications as depicted in Figure 2-3. However, research and development of OWC enabling technologies is out of scope of WP2.

Nevertheless, for the purpose of completeness, a short overview of OWC is reported in the following as complementary to the detailed gap analysis of the radio enabling technologies in Chapter 3. More rigorous research work can be found from, e.g., 6G BRAINS project [BRA20-D21].

2.5.3.1 Brief Overview of OWC Technologies

OWC encompasses different technologies able to address distinct use cases, e.g. Visible Light Communication (VLC), Light Fidelity (LiFi), Optical Camera Communication (OCC), Free Space Optical Communication (FSOC), and Light Detection And Ranging (LiDAR) [CHI+18].

Depending on the considered technology, OWC uses InfraRed (IR), Visible Light (VL), Ultra Violet (UV) spectrum and can provide short, medium, and long range communication distance [CHI+18].

Table 2-9: Wavelength / frequencies used in optical wireless communication.

	Infrared	Visible light	Ultraviolet*
Wavelength	0.1 mm – 760 nm	760 nm – 380 nm	380 nm – 10 nm
Frequency	3 THz – 394.7 THz	394.7 THz – 789.5 THz	789.5 THz – 30 PHz
OWC technologies	LiFi, OCC, FSOC, LiDAR	VLC, LiFi, OCC, FSOC, LiDAR	LiFi, FSOC

* Even if possible, for some technologies, UV is not considered safe for human and affects materials' properties.

Major advantages are:

- Enable privacy by design using the visible part of the spectrum, leading to restrict the signal availability in buildings, potentially enabling cybersecure applications at low cost.
- Hotspot services in ultra-dense networks, and some of them can be long-range ones and provide high capacity backhauling for beyond 5G systems
- Potentially offer wider bandwidths and higher data rates than the achievable ones in RF spectrum, with the size of the IR and VL spectrum together, i.e. about 785 THz
- Very low power consumption (except for UV spectrum), low-cost emitters using lighting equipment, lack of interference with any radio device and network

Major disadvantages are:

- Interference coming from natural light and other light sources makes some of OWC technologies like VLC and LiFi not suitable for outdoor applications.
- Atmospheric conditions such as fog, haze and rain have conspicuous impacts to the link reliability and performance of some of OWC technologies like FSOC and LiDAR.
- The frame rate of conventional image sensors limits the achievable data rate in OWC technologies like OCC and leads to light flickering in case of low frequency VL transmitted signals.
- OWC technologies using the IR and VL spectra requires LOS communication and achieve very limited low data rate in case of NLOS communication using reflection of IR and light, respectively; UV spectrum is not considered safe for human and affects materials' properties.

With the aforementioned technical properties and taking the advantages and disadvantages into account, OWC may be an attractive technological choice in the following applications and to be integrated as a part of future 6G network of networks.

<u>OWC for Wireless Access</u>

Technologies like VLC and LiFi can be used for the deployment of wireless access, e.g., in following scenarios:

- Simultaneous LOS communication and illumination (it is worthwhile noting that light is visible even when not required, and cannot be switched-off, but it can be dimmed while maintaining high data rates; moreover, the achievable data rates are extremely low with NLOS communications, stemming from path loss and multipath effects).
- Short range communication (<10 m) in indoor (whilst in outdoor there are interferences coming from natural light and other light sources).
- Deployment in electromagnetic-sensitive areas such as hospitals, nuclear and power plants, petrochemical sites, and aircraft cabins, avoiding electromagnetic pollution.

- Deployment of different security levels to individual lights or a group of lights and achieving advanced geofencing capabilities for highly sensitive data, due to the characteristic of containing light in buildings (in the absence of windows).
- Railway stations, airports, museums, shopping malls where smart display signboards may be used in these locations and information can be transferred to these displays through LiFi and VLC technology.
- Underwater communications e.g. used for environmental monitoring.

However, the transition from point to point links to full wireless optical networks imposes several challenges, e.g. within each cell there can be several users and therefore multiple access schemes are required; advanced Co-Channel Interference (CCI) mitigation techniques often require that multiple LiFi APs are operated by means of a centralized control mechanism such as 'resource schedulers' within a controller, to adaptively allocate signal power, frequency, time and wavelength resources. The central controller is also in charge of any handover process from the serving cell to the target cell in case of mobility; moreover, connectivity has also to be maintained when users leave a room or the premises and therefore there might be situations when there is no longer LiFi coverage, in which case interworking between LiFi and Wi-Fi can take place in the framework of hybrid LiFi / Wi-Fi networks.

The above-mentioned features, namely multiuser access, interference mitigation and mobility support, are critical research aspects deserving further investigations [Haa18].

<u>OWC for Mobile Wireless Backhaul</u>

OWC technologies connectivity to the core network is achievable with several options and the access network may be connected through wired or wireless backhauling connectivity, feasible with different technologies.

For instance, VLC, LiFi and OCC connectivity to the 6G core network can be provided by e.g. optical fibre connections, ISP networks, FSOC, 6G RAN-based connections, NTN (Non-Terrestrial Network) connections, e.g. satellite links and generally links provided via airborne or spaceborne vehicles for transmission.

FSOC may provide backhaul solutions for cellular networks, VLC, LiFi, OCC, and different types of airplane / ground / satellite connectivity. Although it is normally operated using the Near IR (NIR) spectrum to achieve long-range communication, FSOC can also use the VL and the UV spectra. Generally, illumination is not required in FSOC that often uses Laser Diodes (LDs) rather than Light Emitting Diodes (LEDs) for the transmission. Narrow beams of focused light from an LD transmitter are needed to establish high-data-rate communication links between a transmitter and a receiver. It is possible to achieve transmission rates of 10 – 100 Gbps with FSOC whereas the link reliability is highly dependent on atmospheric conditions such as fog, haze, and rain. If Coarse Wavelength Division Multiplex (CWDM) or Dense Wavelength Division Multiplex (DWDM), which are standard in the fibre optical communication systems, can be utilized, Tbps transmission rate could potentially be achieved [SC20].

<u>OWC for Localization and Sensing</u>

OWC technologies such as LiFi and VLC may provide geolocation services with an error margin in the order of a few centimetres. As an example, they allow for online guided tours following step-by-step the visitors' routes.

Very accurate cm-level indoor and outdoor localization and depth measurements can be performed using OCC technology, which provides non-interference communication and a high SNR even in outdoor environments. Moreover, stable performance is achievable even when the communication distance increases.

LiDAR is an optical remote sensing technology that finds the range of and/or other information about a distant target. It determines distance and other characteristics like size by targeting an object with a laser and measuring the time for the reflected light (a portion of the energy of the transmitted signal) to return to the receiver. LiDAR normally uses NIR and VL. It may target a wide range of materials including clouds, rain, dust, rocks, non-metallic objects and is commonly used to make high-resolution maps. A narrow laser beam can map physical features with very high resolutions (for example, aboard an airplane it can map terrain at 30-cm resolution or better). The purposes of LiDAR are like those of RAdio Detection And Ranging (RADAR), with LiDAR using optical light, whereas RADAR uses microwaves.

Comparison between OWC and RF

OWC offers wider bandwidths and higher data rates than RF, avoids electromagnetic pollution and interference with any radio device and network, enables cybersecure applications and geofencing at low cost (due to the characteristic of containing light in buildings).

RF is less subject to environmental impact and atmospheric conditions than OWC is, and it does not necessarily require LOS communication availability, unlike OWC.

Specifically, a comparison between LiFi and Wi-Fi leads to higher data rates and intrinsic security for LiFi, which on the other side is not suitable in outdoor and does not allow for long-range communication.

FSOC achieves higher data rates and communication distance compared to microwave links, but it is more subject to impacts coming from environment and atmospheric conditions.

Comparing LiDAR and RADAR, LiDAR allows for detection of very small objects like cloud particles, whilst in case of RADAR the detectable object size is limited by longer wavelength; on the other side, RADAR can operate in bad weather conditions, whilst in such a case LiDAR leads to performance degradation.

OWC Coverage and Capacity

Among the OWC technologies, as far as coverage and capacity of commercially available LiFi systems are concerned, the cell size of a LiFi AP (using off-the-shelf light fixture) is around 10 m^2, supporting up to 16 devices and a total data rate up to 150 Mbps in DL and up to 50 Mbps in UL, operating in full-duplex mode and supporting multiuser access and handover process (soft handover and handover between non adjacent APs are used, due to the reduced cell size [HYC+20]). Specific optical components introduced in light fixtures capable of WDM (Wavelength Division Multiplex) would allow for total data rate up to 10 Gbps per AP (1 Gbps / m^2) or even more in case combined laser diodes with optical diffuser are used for the transmission.

LiFi access network (and other OWC technologies like VLC and OCC) may be connected to the core network through wireless backhauling feasible with another OWC technology, i.e. FSOC, with transmission rates of 10 – 100 Gbps, potentially reaching Tbps transmission rate in case of WDM.

With commercially available systems, in terms of OWC technologies for both access network (LiFi) and backhauling connectivity (FSOC), it is therefore possible to support in DL more than 1,000 – 10,000 devices (i.e. 10 – 100 Gbps / 150 Mbps x 16 devices) in an area of around 600 – 6,000 m^2, with an average data rate of around 10 Mbps per device (i.e. 150 Mbps / 16 devices), and more than 3,000 – 30,000 devices in UL in an area of 2,000 – 20,000 m^2, with an average data rate of 3 Mbps per device, whilst in case of WDM capability, at both LiFi and FSOC side, the supported devices are around 1,600 in an area of about 1,000 m^2 (obviously still 1 Gbps / m^2 for backhauling as for access network), with an average data rate of more than 600 Mbps per device (i.e. 10 Gbps / 16 devices, assuming that the number of the supported devices per AP is the same as for commercially available systems).

In the above analysis LiFi has been envisaged as an OWC technology for the access network, since it is a complete wireless networking bidirectional system, supporting seamless user mobility, multiuser access, point-to-multipoint and multipoint-to-point communications, features which are not mandatory for VLC; moreover, VLC uses only the VL portion of the spectrum, whereas LiFi often uses an IR source in UL (so it is invisible to the user) [Jur18].

2.5.3.2 Summary and Relation with WP5

Depending on the envisaged OWC technologies, they may be used for wireless access (in indoor scenarios enabling privacy by design and advanced geofencing capabilities for highly sensitive data, and avoiding electromagnetic pollution), mobile wireless backhaul (providing themselves backhauling connectivity to the core network) and localization and sensing (providing geolocation services and remote sensing technologies with cm-level precision).

A short overview of OWC technologies, together with a quick coverage and capacity analysis, both in DL and in UL, for both access network (using LiFi as an OWC technology) and backhauling connectivity (using FSOC as an OWC technology), has therefore been provided to envisage them in light of their integration in the flexible network of networks from the architecture's viewpoint under WP5 remit, to enable extreme performance in specific use cases.

3 Gap Analysis

This chapter gives the framework for radio system analysis towards 6G operating at upper mmW region for enhanced capacity and improved precision opportunity in positioning. The gap analysis gives an overall view of the key items that are potentially of importance for 6G (sometimes also called as beyond 5G) systems in the radio domain. It consists of sections discussing HW, waveforms, beamforming, distributed MIMO, and radio channel. Not all the tasks have been started by the time of writing this document. That has impact on the viewpoint given in different sections. The different sections of this chapter have many complex interdependencies, and this document highlights some of those as shown in Figure 3-1. Some of those are described with details and large set of references in [PAB+20]. By doing this analysis during the project, we also aim to propose a balanced set of system performance aspects for the 6G system standardization, which could match the use case requirements to feasible radio platform solutions in an effective and power efficient manner trying to match top down and bottom up approaches as well as possible. As many of the potential new use cases will not necessarily require major enhancements from the 5G evolution, this analysis is focuses mostly on the cases which cannot be solved using the anticipated 5G evolution. Therefore, most of the focus is on extremely high data rates and due to that carrier frequencies of 100 – 300 GHz. In addition, some radio system items like distributed MIMO are discussed without this frequency limitation. Such novel features can be also applied at frequencies below 100 GHz.

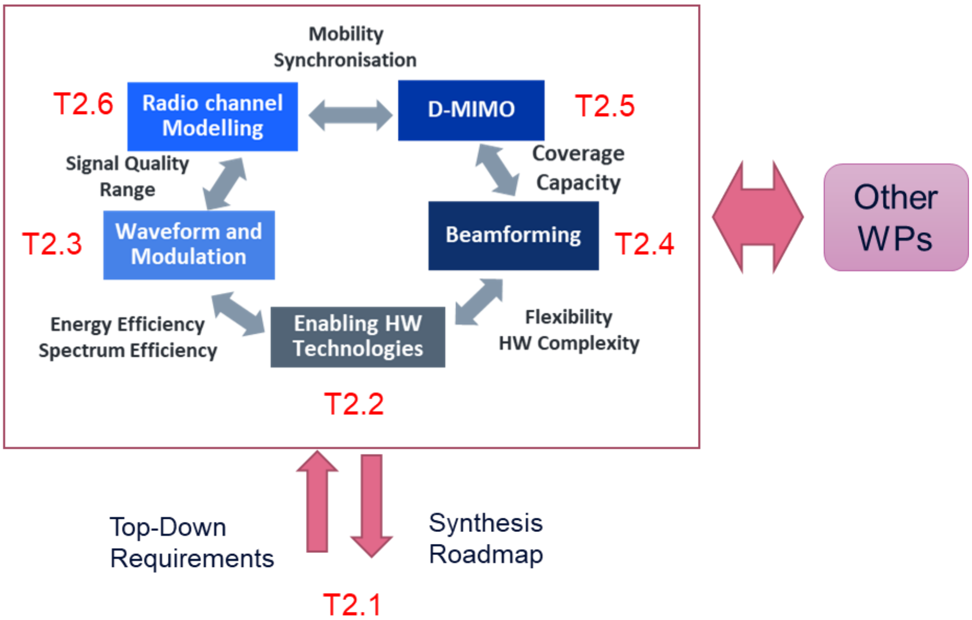


Figure 3-1: Simplified view of interdependencies between technical areas.

The radio system design requires highly multi-disciplinary skills from algorithms to details of physical components and phenomena. In addition, many of the necessary technologies do not exist yet and complex interactions are difficult to predict. A simple, logical system model in Figure 3-1 describes the approach where the first step is to analyse major aspects that need to be taken into account in co-design and co-optimization. Basically, the model is very similar as would be needed for in 5G NR mmW as well. However, due to rapidly growing complexity and practical technical constraints at extremely high-speed communications there is a need to provide a comprehensive but highly abstracted view over technology boundaries. Missing key technology constraints as part of the analysis will easily lead to misconceptions when defining system performance, power efficiency or other KPIs in standardization. At upper mmW (100 – 300 GHz) or THz frequencies which are needed for extremely high-speed communications and accurate positioning, the design of the radio system must be increasingly hardware-aware to avoid the above-mentioned pitfalls. The gap analysis is the basis for the more detailed analysis in the next steps of this project. The descriptions in this chapter will have overlaps that are necessary and are basis for the further work to combine those under the same umbrella.

One of the key goals of this work package is to bring some advanced methods to tackle this challenge in case of 6G when we still have quite many degrees of freedom in system concept. For example, waveforms can be selected based on HW technology capabilities, positioning needs and other aspects without legacy of previous choices at upper mmW region. Of course, these changes will be done only if it avoids fallbacks and brings major technical benefits.

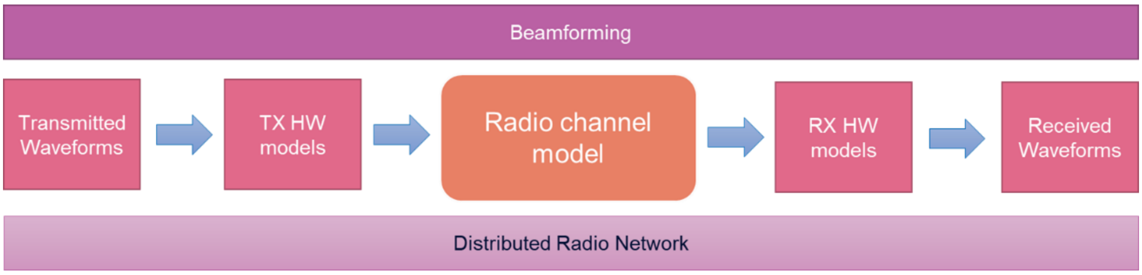


Figure 3-2: System model for 6G radio analysis from end-to-end link perspective. Beamforming, MIMO, and distributed radio network need to consider the whole signal path and limited isolation (i.e. coupling) between orthogonal channels.

3.1 Initial Technical Requirements Including Data Rate Targets

The document D1.2 [HEX21-D12] gives general requirements, like use cases, for the 6G system, which are analysed more in detail towards technical requirements in this document in Chapters 2.1 and 2.2. Additionally, document D1.2 [HEX21-D12] describes aspects of spectrum use that will not be described here.

Use cases and anticipated data rate targets give a framework for a radio hardware analysis, which kind of radios will be needed in the 6G era. The 6G radios will be implemented partly as an evolution of 5G mmW radios and partly based on new innovations. In hardware this means analysis from data rate and range requirements, giving targets for link performance, to physical properties of the HW technologies and radio channel. The radio HW cannot be considered as a simple black box with a limited property set as in previous telecommunication generations. The multi-antenna implementations and the usage of beamforming, especially hybrid beam forming, have changed the radio hardware design and analysis principles. The capabilities and expected implementation limitations of the radio HW need to be considered for a successful concept development of 6G.

The set of data rate requirements coming from different use cases constitute a key specification for the wireless platform HW including RF and digital processing. As use cases are being defined by the time of this document and analysis for detailed requirements related to required data rates etc. is still on-going it is not possible to include very detailed targets here. Hence, at this stage studies have been started but move forward with highly generic goals and bottom-up technological capabilities. However, based on the general and initial goals given to 6G that are based on 5G capabilities as well as foreseen technological progress for example according to Edholm’s law [KP13] it is expected that the maximum data rates for the forthcoming 6G system will be in the range of 100 Gbps even up to 1 Tbps in specific scenarios. These two targets are highly dependent on the use case requirements, but both are extremely challenging even theoretically for commercial systems by 2030’s even in maximum link performance.

Based on the initial targets and use case information and technical system capabilities, technical requirements can be derived as starting points for the 6G radios. These are presented in Table 3-1 and are the basis for the following analysis. The feasibility of commercially viable implementation will then depend heavily on many aspects including mobility, power source (battery, fixed supply,), etc. Therefore, refinements for many details on the relevance and applicability will be needed in practice. Here we will also describe peak data rates in optimal conditions without other users present nearby. In case of cellular networks, the capacity is shared between many users and impacted by many aspects like mobility, HW and radio channel will have major impact on the true achievable capacity. This approach will also help to define models towards system capacity with more realistic HW and radio channel assumptions in the future.

Table 3-1: Initial technical requirements for the 6G extreme data rate radios.

Parameter	First wave 6G radio requirement	Long-term vision for 6G radio
Data rate (R)	100 Gbps	1 Tbps
Operational/carrier frequency (f_c)	100 – 200 GHz range	Up to 300 GHz range[3]
Radio link range (d)[4]	100 – 200 meters	10 – 100 meters[5]
Duplex method	Time Division Duplexing (TDD)	TDD
Initial device class targets	Device to infrastructure, mobile backhaul/fronthaul	Infrastructure backhaul/front haul, local fixed links, and interfaces (data centres, robots, sensors, etc.)

3.2 Radio Considerations for Extremely High Data Rate Links

This section considers aspects that are critical for defining key performance indicators and related parameters in the design extremely high data rate radios. The section starts with the analysis of bandwidth requirements for supporting 100 Gbps – 1 Tbps radios and different options for channelizing information. Then mobility aspects and examples of state-of-the-art link trials are presented, which are followed by the discussion of range and power consumption estimation approaches. At last, time domain aspects in terms of duplex schemes are considered. The topics discussed in this section will provide the foundation for the hardware modelling. This is rquired for the parametrization of different 6G radio technology and concept alternatives.

3.2.1 Bandwidth and Channelization

The used signal modulation will affect the needed RF BandWidth (BW) as shown in Table 3-2 for achieving 100 Gbps data rates. This analysis assumes one signal stream, and when more orthogonal signal paths are added, the RF signal bandwidth requirement can be divided between

[3] Initial view on radio technology capability perspective made as target for the project. Feasibility to go higher frequency followed during the project.

[4] Link range is always a trade off with at least data rate and range targets, technology, cost and power consumption. If cost or technology are fixed, higher frequency and wider bandwidth will lead to a shorter range. More details on this tradeoff will be given in Section 3.2.

[5] Backhaul links may need significantly longer range and can be taken specifically into account later. In this case initial target is done for other than fixed backhaul applications.

different channels (MIMO, frequency, etc.). It can be seen from the table that the bandwidth for 16-QAM modulation or higher is in the range of 10 % at frequencies of 150 – 300 GHz, which is seen as the target of RF circuitry design. The BaseBand (BB) bandwidth presents the signal BW that is used in Analogue to Digital Converters (ADC) and Digital to Analogue Converters (DAC). When targeting towards Tbps the required data rate increases accordinglyas shown in Figure 3-3.

Table 3-2: 100 Gbps data rate signal bandwidth analysis.

Modulation	bits / symbol (b/S), no coding	bits / symbol (b/S), 5/6 coding	RF BW no coding (GHz)	RF BW 5/6 coding (GHz)	BB BW no coding (GHz)	BB BW 5/6 coding (GHz)
BPSK	1	0.83	100.00	120.00	50.00	60.00
QPSK	2	1.67	50.00	60.00	25.00	30.00
16-QAM	4	3.33	25.00	30.00	12.50	15.00
64-QAM	6	5.00	16.67	20.00	8.33	10.00

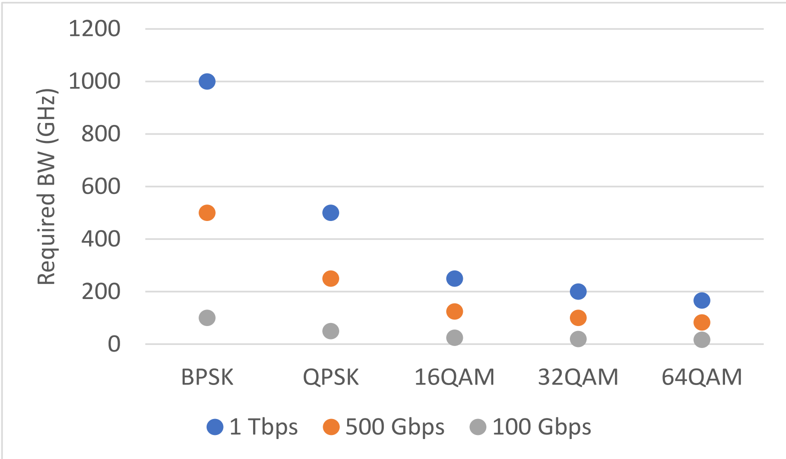


Figure 3-3: Required total bandwidth for different uncoded modulations for different data rates. Bandwidth will not include any guard bands or filtering impact.

Then channelization of the bandwidth is needed when relative bandwidth is impractical or more often restricted due to spectrum regulation. Particularly, cellular systems are typically operated in dedicated bands under strict regulations [HEX21-D12]and bandwidth thus has become extremely limited and split over different bands. On the top of that individual bands are split between many operators. It is evident that in such scenarios the spectral efficiency has become the most important criteria. As a result, complex schemes, like multi-band carrier aggregation over many bands, have become de facto in 4G and 5G and individual channels are below 1 GHz even in 5G NR at lower mmW region. When targeting at 100 – 1000 Gbps rate, it is clear that we will have major gap not only in implementation but also in regulations. It will not be simply possible to split the transmission to tens of hundreds of channels[6] even if MIMO is adopted due to, e.g., lack of contiguous bandwidth or limitation of hardware. MIMO availability depends on the orthogonal channels between transmitter and receiver or in case of distributed MIMO on the number of serving radio nodes under the same coverage area. The number of available orthogonal channels depends also on the properties of radio channel. Therefore, studies carried out in Hexa-X and other relevant projects are needed to define corresponding practical constraints. However, very likely the number of signal paths will be lower at higher frequencies and bandwidths because

[6] Channel in generic sense means any part of contiguous spectrum that can be used to transmit information over certain bandwidth. Channels can be split for different users in frequency, spatially based on MIMO rank, code or other means. In many cases signals require dedicated signal paths also from HW perspective but not always.

highly directive communication is required even for the strongest, many times LOS, path. Therefore, the NLOS paths are usually not strong enough to exceed the noise of a wideband receiver with sufficient dynamic range, which will limit the opportunities for using MIMO and diversity.

The most common approach optimizes the radio transceiver capacity by using dual polarized antennas which are collocated and are fed from different antenna ports. This kind of dual polarized antennas are currently used in 5G mmW radios as presented in [SSL+20]. The usage of dual polarized antennas would thus divide the required RF BW in half. But then two RF parallel transceivers are needed doubling the power consumption as in any MIMO scheme. Further, the antenna isolation between antenna polarizations needs to be adequate as well as the radio channel isolation between polarizations. The needed isolation between polarizations vary according to the used modulation and higher order modulations will require higher isolation. The required isolation between polarizations needs to be studied in detail when first antenna designs are available. In general, this isolation issue is quite similar as in case of generic MIMO. Only the almost non-existent power difference between the channels is reducing the dynamic range problem that needs to be solved in case of directive beams with spatial filtering.

Spectral efficiency also makes a direct trade-off with the required Signal to Noise Ratio (SNR) for detection. The higher the required SNR, the shorter the respective range becomes both due to transmitted power limitations at high frequencies as well as added noise. These two aspects basically attract to use lower frequencies and increase spectrum efficiency even further. However, this cannot be done infinitely and even in SISO case the maximum SNR even in LOS conditions will be limited. In case of fixed i.e. static links we can expect 512-QAM as baseline, but mobility and larger bandwidth/higher carrier frequency will bring this down to 64-QAM or even less. This is still much better than On Off Keying (OOK) or other single bit modulations but making a trade-off how BW can be narrowed down. Still 25 – 30 dB SNR requirement in practical conditions will be a tough goal, especially for battery-driven devices.

Our previous discussion has given an overview of major challenges facing while carrying out channelization. In summary, the main constrains are the availability of spectrum, channel properties and technological capabilities in terms of transmit power, noise, bandwidth, carrier frequency, filtering, beamforming, and isolation of the channels, all of which must be tackled at the same time. Therefore, channelization of extremely wideband signals is in general one of the key challenges towards 6G.

3.2.2 Mobility aspects

The fast movement of the mobile terminal will create Doppler frequency shift of the operational centre frequency which is relative to the speed of the movement and the operational frequency. The Doppler frequency shifts for expected 6G frequency bands have been calculated and reported in Table 3-3. The Doppler frequency Df is calculated with

$$Df = \frac{Dv}{c} f_0, \tag{3-1}$$

where Dv is movement speed of the terminal, c is the speed of light and f_0 is the operational frequency. It can be seen from the results that significant Automatic Frequency Control (AFC) range is needed. The AFC control starts from Hz range until 100 kHz when 300 GHz frequency operations are expected. When, a very wide AFC control is needed, the noise from the control signals and operational voltage need to be controlled with a careful circuit design. In case of Vehicle to Vehicle (V2V), the numbers can be even twice as high as the ones shown. Very large bandwidths will also be impacted by a varying Doppler shift over the frequency band.

Table 3-3: Doppler frequency shift with varied device movement speeds at different operational centre frequencies.

Action	Speed (km/h)	30 (GHz)	60 (GHz)	100 (GHz)	150 (GHz)	200 (GHz)	250 (GHz)	300 (GHz)
walking	3	83 (Hz)	167	278	417	556	694	833
running	7	194	389	648	972	1296	1620	1944
biking	30	833	1667	2778	4167	5556	6944	8333
car, highway	100	2778	5556	9259	13889	18519	23148	27778
car, autobahn	250	6944	13889	23148	34722	46296	57870	69444
high speed train	500	13889	27778	46296	69444	92593	115741	138889 (Hz)

The mobility of the device relates to its physical displacement or rotation. The mobility affects the number of needed handovers to guarantee continuation of the communication. The device's velocity relates to its constant physical movement such as travelling speed of the user who carries the device.

3.2.3 Link Level Performance Examples

If we look at the state-of-the art from data rate perspective with respect to range, there are some demonstrations that can achieve data rates close to or even above 100 Gbps over an individual radio link. Most of the public demonstrations have been tested using dedicated and very expensive data capture equipment i.e. not very realistic implementation for a commercial system for masses. However, there are some solutions implemented using SiGe BiCMOS, CMOS, III-V, or photonic techniques that have shown basic functionality in most cases ~1 – 10 m range and in some cases even longer. However, the demonstrated links are typically fixed and use highly directive antennas even for short ranges. It also needs to mention that these proofs of concepts lack any beam steering capabilities. Therefore maturity of such trials is still low and bridging the gap to 5G NR mmW solutions, like [STH+17] and [DKO+18], requires a lot of technology research and development starting from semiconductor and technologies and basic building blocks to architectures and concepts that provide adequate trade-offs towards commercialization. Figure 3-4 shows some recent results from publications. The detailed references to those can be found from [PAB20] and [GFF+21]. Link capacities beyond 139 Gbps have been demonstrated over 1.5 km with commercial microwave radios at the E-band (70/80 GHz) using spatial multiplexing (MIMO) in a static LOS scenario [EAB19, CHS+19]. Very recently, 5 Gbps have been demonstrated reliably at the frequency range 92 – 114 GHz over 1.5 km and 10 Gbps over 1 km, without using spatial multiplexing (SISO) [EAB21]. Both demonstrations target point-to-point application and are based on mmW modules with III-V technology (GaAs pHEMT). While it is still possible to push the limits of what is possible below 100 GHz a little further, moving consistently towards data-rates above 100 Gbps at scale will require higher bandwidths that are only available well beyond 100 GHz. An example is the outdoor link installed for long-term channel measurement using a carrier frequency at 150 GHz [MLV+18]. Both SiGe [LHE+19] and InP [VHC+18] technology have been used in development of modules in this frequency range.

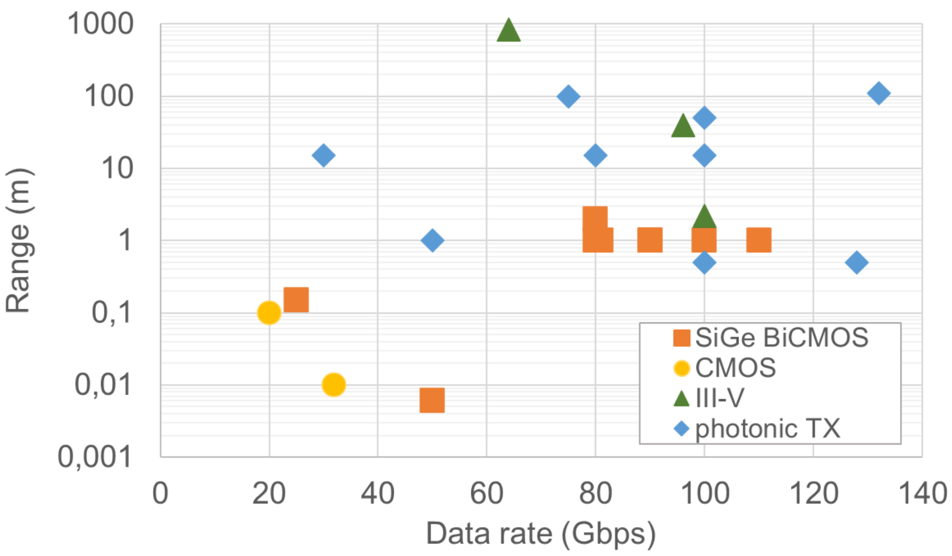


Figure 3-4: Link trials for very high data rates.

3.2.4 Range

Link range becomes more and more critical for high data rates that will be using higher carrier frequency. Range using the classical link budget analysis can be given in decibels as

$$P_{RX} = P_{TX} - L_{path} - L_{fade} + G_{TX} + G_{RX}, \tag{3-2}$$

where P_{RX} is the received power (in case of maximum range called as sensitivity), P_{TX} is the transmitted power, L_{path} is the path loss in LOS conditions, L_{fade} describes the fading margin (or any other additional path loss factor) and G_{TX} and G_{RX} are transmit and receive antenna gains, respectively. The antenna gain contains both gain of the antenna element and possible array gain. In case of transmit arrays, one must also note that the transmitter power of individual Power Amplifiers (PA) and total Effective Isotropic Radiated Power (EIRP) can consist of n antennas and m individual power amplifiers where n and m may not be the same. Also, highly directive antenna elements, like lenses, horn or reflector antennas behave differently from antenna arrays. Therefore, (3-2) depends on the RF transceiver architecture. The same applies also for the receive power. If we focus on LOS, we can ignore L_{fade} term initially. That is important especially in case of MIMO opportunity, but a more detailed model of radio channel as well as an approach different than SISO according to (3-1) must be taken. But for LOS it is sufficient to assume that path loss is

$$L_{path} = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right), \tag{3-3}$$

3where d is the link distance and λ is the wavelength. We may assume based on (3-3) that the link range is reduced as a function of frequency. This common assumption is true for an individual antenna element with the same gain and caused by the fact that the physical size of the antenna is getting smaller. If we keep antenna aperture i.e. effective radiated area the same, we can compensate that loss using an antenna array of the same aperture. Of course, it has an impact on the radiation pattern and thus changes the way radio networks will be designed. 5G NR FR2 (lower mmW bands) already made the change. But due to different technical trade-offs we must apply this quite differently at bands that will require very large antenna apertures/gains. Therefore, optimal antenna array concepts and architectures are also heavily dependent on the frequency, steering capability etc. and cannot directly be scaled from 5G to 6G.

The dimension that is missing from (3-2) and (3-3) is the relation of received power to achievable data rate. Receiver sensitivity depends directly on the bandwidth (B), noise figure of the receiver noise figure NF and required SNR or Signal to Noise and Distortion Ratio (SNDR), Signal to Interference and Noise Ratio (SINR) or whatever term we wish to use. Therefore sensitivity (P_{sens}) representing R_{RX} in (3-2) in dBm scale is

$$P_{sens} = 10\log_{10}(1000\,kTB_n) + NF + SNR_{min} - G_{DSP}, \quad (3\text{-}4)$$

where k is Boltzmann's constant, T temperature in Kelvins, B_n noise bandwidth[7], NF noise figure of the receiver, SNR_{min} minimum SNR to receive specific modulation with requested quality (Bit Error Rate (BER), Packet Error Rate (PER), etc.) and G_{DSP} digital processing gain taking into account coding and some implementation margin. Also, transmitter power (P_{TX}) will not depend only on PA but also on waveform, technology, bandwidth, carrier frequency, losses between PA and antenna, etc. Therefore, the transmit power from the system level perspective needs to be written as

$$P_{TX} = P_{sat} - P_{BO} - L_{ant-PA}, \quad (3\text{-}5)$$

where P_{sat} is the saturated (maximum) output power of the PA, P_{BO} is the back off needed from the P_{sat} to achieve the required SNR (or in case of transmitter Error Vector Magnitude (EVM)) for certain waveform and L_{ant-PA} is the loss between PA and antenna not included in antenna element or array parameters. Both saturated power and back off are highly technology and frequency dependent parameters that will be discussed later.

Textbook formulas (3-2) – (3-4) include a lot of details that are dependent on the requested data rate and the used technology. Basically, the former ones are well known leading to shorter link distance at higher data rates. But already in 5G NR FR2 and even more in the anticipated data rates for 6G, the latter becomes more and more a concern. Section 3.3 assess this part with more details. For the sake of gap analysis, we must address the somewhat hidden dependencies of (3-2) – (3-5). Based on link level analysis, for example as shown in [RKL+20], achieving even 10 m link range for 100 Gbps will be challenging if we base the assumptions on 5G NR FR2 considerations and technologies available for lower mmW range. As wider bandwidth demands will result to higher carrier frequencies the technological boundaries will be much more prominent in use cases needing extremely high data rates.

To address some of the key dependencies still in a simplified manner Table 3-4 lists items and parameters to be considered in system, environment and technology dependencies. Note that this list is not comprehensive. As stated earlier the last category will need more attention than in previous wireless generations as dependencies are complex and high carrier frequency and bandwidth are together stretching technology boundaries. Some more detailed notes will be given in the following sub-sections. But in general, all these aspects will impact the performance, cost, and power consumption many times in highly unfavourable manner. Therefore, key part of the 6G radio design is to find appropriate compromises.

New parameters related to RF, analogue and digital constraints not listed earlier include digital gate delay (t_{Gate}), clock frequency (f_{clk}), clock jitter Δt_{jitter}, phase noise N_{ph}, quantization noise N_q, maximum signal level V_{max}, other signal dependent non-idealities or distortion components D_{other}, mutual interference i.e. cross-coupling between channels I_{mutual}, transition frequency of the transistor f_T, frequency of unity unilateral gain f_{max}. It is a well known fact that all of these tend to worsen when frequency is getting higher. The main question for 6G is what are the ones that really matter most and how big is their impact on performance, cost, and power consumption. This deliverable will focus mostly on some key parameters. It is recognized that implementing a generic and frequency/bandwidth scalable model is, in practice, very difficult if not possible at all. However, in the next phase these dependencies could be mapped such that the model will give

[7] Equivalent noise bandwidth is in case of OFDM in practise equal to signal bandwidth but is somewhat wider for example in case of raised cosine filtering.

valuable and to certain extent accurate insights on the design choices in system level. And many of the individual parameters can be benchmarked to give valuable directions. In many areas more refined and specific studies are valuable to support the system analysis better than today and various architectural choices will make comparison more difficult.

Table 3-4: Simplified dependencies of parameters impacting on range for gap analysis.

Parameter	System dependencies	Environment dependencies	Technology dependencies
Data Rate	B, SNR, coding, # of channels	Shannon limit as capacity	t_{Gate}, f_{clk}, Δt_{jitter}, N_{ph} , N_q , V_{max} , I_{mutual}
Transmitter power	f_c, P_{BO}	T (temperature)	f_{max} (1, P_{sat} , P_{BO} , L_{ant-PA}
Path loss (2		LOS, NLOS, reflections, spectrum availability	reflection and materials
Antenna gain	antenna, array architectures		technology, materials, array architecture
Receiver noise	B_n, f_c	T	f_T (1
Power consumption	all above	all above	all above
Cost	all above	all above	all above

1) f_{max} and f_T are simplified expression to indicate technology dependence
2) Different for each orthogonal path/stream/channel

In addition to the general analysis given above, it should be noted that link range is also a use case dependent issue. The required data rate, BER, spectrum efficiency and link availability, for instance, can be very different for wireless access (e.g., mobile UEs) and for fixed services (e.g., mobile backhaul). In case of Point-to-Point links for wireless fronthaul/backhaul, the link range may be substantially extended by applying highly directive antennas with a gain as high as +55 dBi. The downside of using such high gain antennas is the challenges in alignment and the required mast stability. Automatic mast sway compensation has become an interesting research topic recently. It is likely that upper mmW and THz antenna arrays will be needed in the future even for PtP systems to simply provide beam steering possibility for mast sway compensation.

However, the required high availability for PtP limits the link range. This is particularly true when using carriers beyond 100 GHz due to the large atmospheric fading such as rain attenuation. To give an idea of what link range is practically realistic, Figure 3-5 plots the calculated link range versus the system gain (defined as $P_{TX} + G_{TX} + G_{RX} - L_{all\,fade} - P_{Rx,sens}$) using a 155 GHz carrier and taking into account rain attenuation in the path loss $L_{all\,fade}$. The link range is very much rain intensity (given in mm/h) and availability dependent [EHC+17]. Considering the limited P_{TX} at upper mmW, an optimistic system gain of 155 to 170 dB can be expected using 50 dBi antennas, which according to Figure 3-5 supports a link range of typically less than 2 km if four “9s” availability is required for a link location in a 20 mm/h geographic rain zone.

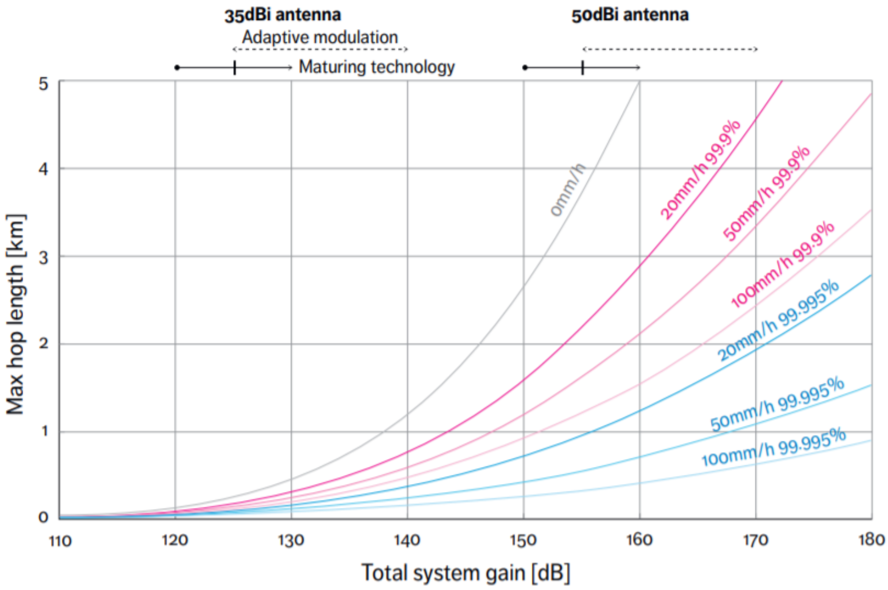


Figure 3-5: Calculated range for LOS point-to-point links vs systems gain using 150 GHz carrier. Link availability (given in percentage) expresses the portion of a year when the link is functionally connected. For example, a 99.995% availability means that the total outage time in a year is no more than 25.6 minutes.

3.2.5 Power Consumption

Power consumption is probably one of the most complex items to analyse in a system that is scalable in terms of use cases, bands, space, time domain behaviour etc. In HW implementations, focus has been in most cases limited to PA efficiency and output power and some other RF and digital properties. When moving already to 5G NR and Gbps data rates Analogue-to-digital conversion, digital signal processing and large parallelism in phased arrays has made characterization more complex and role of PA power consumption as the only significant parameter is reduced. For that reason, transmitter linearization is, e.g., more focused on improving performance (i.e. SNR or EVM) than minimizing the system total power consumption. This trend will continue in the future and architectural choices could have major impact on the result.

If we will make one typical 5G NR architecture assumption (i.e. to transmit certain number of data streams, each having dedicated RF beamformer of the same size), power consumption of RF and stream specific digital processing for multiple data streams can be written as

$$P_{d,link} = n_{str}\left(P_{d,TXDFE} + P_{d,DAC} + P_{d,TXa}\right) + n_{str} \cdot n_{ant,TX}\left(P_{d,RF,TX} + P_{d,PA}\right) + n_{str} \cdot n_{ant,RX}\left(P_{d,LNA} + P_{d,RF,RX}\right) + n_{str}\left(P_{d,RXa} + P_{d,ADC} + P_{d,RXDFE}\right) + P_{d,LO}, \quad (3\text{-}6)$$

where n_{str}, $n_{ant,TX}$, and $n_{ant,RX}$ are number of data streams, Tx, and Rx antennas, respectively. Power amplifier ($P_{d,PA}$) and low noise amplifier ($P_{d,LNA}$) power dissipations have been separated from common RF paths ($P_{d,RF,TX}$ and $P_{d,RF,RX}$) and joint path for each stream includes digital front-end ($P_{d,TXDFE}$ and $P_{d,RXDFE}$), DAC ($P_{d,DAC}$) and ADC ($P_{d,ADC}$), and common analogue ($P_{d,TXa}$ and $P_{d,RXa}$) components. $P_{d,LO}$ is a combined quantity that includes all the power needed for Local Oscillator (LO) signal generation including high frequency synthesizer (Voltage Controlled Oscillator (VCO) and Phase Locked Loop (PLL), possible multiplication up, power distribution to different mixers, LO buffering and also reference clock generation. LO generation has many architectural options and therefore without biasing to any of those options that may lead to somewhat different conclusions this part has reduced to a single quantity.

Equation (3-6) is once again distance, data rate, technology etc. dependent. The basic idea is simple. But defining realistic values for each of these and over different distances in a scalable manner is far from trivial. Equation (3-6) is missing also common digital processing of MIMO streams and anything that relates to detection, coding, interleaving etc. Those could be added as a single term for transmit and receive functions if estimates are available.

Even more comprehensive efforts to address some behavioural RF models, like PA, have been done also introducing a term accounting for system efficiency [CUN19]. Such an approach if understood properly can give highly valuable means to consider system efficiency also from energy consumption perspective. Optimizing energy will lead to quite different optimum compared to data throughput or capacity driven target.

Finally, dynamic behaviour impacting both the data rate and the total average power consumption should be understood in system architecture context. A properly designed radio or radio system tries to be in off or idle state whenever possible. Therefore, average power drain can be written as

$$P_{d,avr} = \eta P_{d,link} + (1 - \eta) P_{idle}, \tag{3-7}$$

where η is the duty cycle of the active transmission and P_{idle} the idle or off state power consumption. In a practical radio system, the corresponding state machine will have also other possible states that could be modelled accordingly. For example, in case of TDD, Tx and Rx states must be differentiated.

The model that looks extremely simple requires highly multi-disciplinary approach for finding appropriate estimates. For that reason, power consumption has been one of the major problems in all digital communications generations since 2G at least in the early phase of the system. Technology and careful optimization have led to satisfactory performance gradually with evolution. However, even this is not as straightforward as earlier due to increased complexity of the systems like 5G NR or future 6G. Therefore, estimates will require careful analysis and comprehensive approach over different technology domains in Open Systems Interconnection (OSI) stack and they are both use case and protocol dependent. At the early phase of the system design simplified models can give guidance to the right architectural choices but generalizing those is rarely possible.

3.2.6 Time Domain Aspects

For highly integrated upper mmW application, the TDD operation is envisioned. The main motivation to use TDD over FDD from the hardware perspective is that no diplexer is needed. At the time of writing this document only waveguide-based implementation of duplexers in this frequency range exists [ZGC+20]. As we envision highly integrated modules of the antennas and the related LNAs and PAs as well as a large number of antennas we do not think FDD implemented with waveguide-based diplexers do fit the envisioned formfactor of either the base station or the mobile device. Another aspect setting TDD and FDD apart is the channel reciprocity. As the same frequency band is used for transmission and reception in TDD mode, the channel excluding the frontend can be assumed to be the same. To exploit this effect the transmitter and receiver need to calibrate the difference between the transmit and receiver frontend. For upper mmW system this is especially attractive in the context of beamforming as the optimal transmit beam can be inferred from the optimal receive beam and vice versa.

In a TDD mode, the antenna can be used for both transmission or reception or either. In the case that the antenna is used for both a T/R switch is necessary. Examples in the frequency range of 110 to 170 GHz show that such switches can have an Insertion Loss (IL) in the range of 2 – 4 dB while providing an isolation in the range of 20 – 40 dB [KMK19]. Additional losses of the connection of the PA to the T/R switch, as well as the connection of the T/R switch to the antenna need to be considered. As providing sufficient output power of the PA is already a challenge (see Section 3.3.1) all additional losses of delivering this power to the antenna should be avoided. This can motivate the use of separate antenna arrays for the transmitter and the receiver. However, in such a system the channel cannot be reciprocal, therefore all these aspects need to be carefully considered to find the optimal system design based on the performance requirements and the limitations of the RF front-end.

In-Band Full Duplex (IBFD) was extensively studied during the timeframe preceding 5G standardization. The main challenge for IBFD is self-interference, as the power difference between the transmit and receive signal is in all cases large. As the power difference can easily be above 100 dB, proper suppression, or cancelation of the self-interference in the analogue and the digital domain are necessary to achieve sufficient performance. Isolating the receive antenna from the transmit antenna as shown in [KHI+16] is one way to supress the self-interference in the analogue domain. Another way is to introduce an active cancellation circuit in combination with other techniques to isolate the receiver from the transmitter [ERR+17]. To avoid saturating the LNA the analogue cancelation needs to occur before the LNA. For the digital self-interference cancellation, it needs to be guaranteed that a dynamic range sufficient to cover the self-interference plus the signal of interest is available after the A/D conversion. Otherwise, as the self-interference has in many cases a power level higher than the signal of interest, the later could be below the quantization noise. Note that all these systems operate in a narrow band relative to the carrier frequency. Translating these results to upper mmW frequencies will not be straightforward. The main challenge is the larger relative bandwidth, the envisioned number of antennas and the limited available dynamic range in the digital domain.

3.3 HW Related Gaps

This section goes deeper into some hardware related gaps. However, many of these aspects reflect directly topical items in waveforms, phased arrays, distributed MIMO, and radio channel, especially in case of link performance discussion. The focus is on key components or their performance aspects including transmit/power amplifier power delivery capability, receiver noise, phase noise, data converter non-idealities, digital signal processing challenges and antennas. All of them define practical constraints on the performance and power consumption that need to be considered in the radio architecture, link, and system design. At the end of the section an approach to model flexibly RF transceiver architecture towards 6G radios is being considered. That will be based on reference architecture or reference architectures for different kind of radios needed for different purposes. However, this document is only giving conceptual idea how to model different aspect together. Future work will then focus on the modelling itself to evaluate potential and viable technologies against 6G targets.

RF non-idealities are strongly dependent on underlining technologies and frequency/bandwidth needed. This section briefly introduces some of the key parameters that have direct impact on the achievable data rate and link range, which in their turn directly have an impact on the 6G feasibility to achieve data rates beyond current 5G NR. One must remember that these relations are also directly associated to cost, power consumption and form factor of the devices used. As shown earlier there are already prototypes that reach or even exceeds 100 Gbps in specific cases. Also, frequencies well beyond 5G NR FR2 bands have been utilized for other purposes. Therefore the discussion is not whether something would or would not be possible at all, but what are the compromises and opportunities we need to consider from the beginning in defining the gaps in a way that will lead to more feasible solutions (economically and from the energy efficiency perspective) for various static and especially at least somewhat mobile applications. This is then basis for more refined analysis in the future that will bring these aspects better under the same framework. Modelling these dependences is not straightforward and taking different trade-offs into account requires more comprehensive approach and deeper domain specific expertise when technology boundaries are approached. However, the analysis below is not fully covering yet compatibility of different technologies and complexity when interfacing between those cases. Therefore, we need to interpret the following aspects still as a limited view that will give general guidelines, but such simplifications should not be generalized in absolute scale for system level analysis.

3.3.1 Transmitted Power

Generating sufficient power is probably one of the most important and well-known challenges in wireless communications. While the focus at lower frequencies (like 5G NR FR1) is mostly on efficient power generation and out-of-channel interference minimization, at mmW especially when going towards THz region the biggest bottleneck is simply to generate sufficient power to achieve decent link range even as a part of antenna array. This is one of the reasons why there has been the so-called THz gap between radio and optical communications. This gap is constantly reducing but will not disappear completely. It may be possible to use spectrum also in the formerly named ‘gap region’ but there is inevitable an inevitable cost associated to it in terms of the amount of power we can generate in a cost and power efficient manner. Here we focus only on approaching the problem from microwave spectrum angle. In RF performance, the power is limited by the capabilities of transistors implemented using different semiconductor technologies. Although other types of power sources exist, PAs using the same technology or at least having packaging capability tightly with the rest of the electronics will be the most probable solutions for 6G as well. Also, technology options still in the academic research and not yet reaching competitive results in power amplifiers published in major microwave and integrated circuit design conferences are likely not mature enough for commercial use by 2030’s.

Professor Wang’s group at Georgia Tech has published in 2018 a comprehensive survey on published power amplifiers since 2000. It’s newest version 5.1 available by the time of this report is expanding the data towards 6G as well [WHM+21]. Due to its comprehensive nature it has become the most prominent reference for technology capability analysis in the field. Figure 3-6 shows maximum power delivery capability of all different technologies for PA’s and other means to generate power using semiconductor technologies. Trend is declining as a function of frequency and has a steeper slope practically in all technologies above 100 GHz. This is due to the fundamental speed limits of the technology, often simplified only as f_{max}. The performance differs between semiconductor technologies. However, in Figure 3-6 this is visible already in a higher abstraction level when complete PAs have been built from those transistors using different topologies, ideas etc.

Values in Figure 3-6 are given as saturated output power where the PA is already in deeply non-linear state and therefore not providing decent SNR/EVM for most of the modulation schemes. backoff required for specific modulation according to (3-4) must be considered reducing transmitted power even further. In case of OFDM that can be even in the range of 10 dB while single carrier modulation schemes can reduce the level up to few dB’s depending also on filtering and digital clipping. Anyways, assuming P_{sat} as realistic transmission power is a serious error in most cases. In addition, different technologies and design choices with single technology will lead to very different non-linear behaviour on the smoothness of non-linear distortion curve. Therefore, these trade-offs are difficult to analyse and specifically generalize. Still an estimate within few dBs even in the first analysis, as in [RKL+20], is better than nothing although even this has a major impact on the link range estimate accuracy as well. And relative numbers are giving the correct trend anyways. Also, similar rapid annual improvement just due to technology scaling according to Moore’s law as in digital cannot be expected. Trend towards faster transistors leads to smaller dimensions that have typically negative impact on power delivery capability. Also, rapid improvement in other key technology parameters is not foreseeable automatically. Advances will require dedicated scientific and engineering work in all domains from devices to architectures is difficult to predict over time, but we cannot base system analysis on major quantum leaps in this area.

If we look at trend lines in Figure 3-6, most of them follow quite closely 10 dB per decade curve from 1 GHz to ~100 GHz and then the slope becomes even steeper clearly showing the most visible gap when addressing extremely high bandwidths and thus carrier frequencies. The numbers shown in this context are typically done for narrowband signals (close to sine wave) and things will not go any easier with wide band approaches.

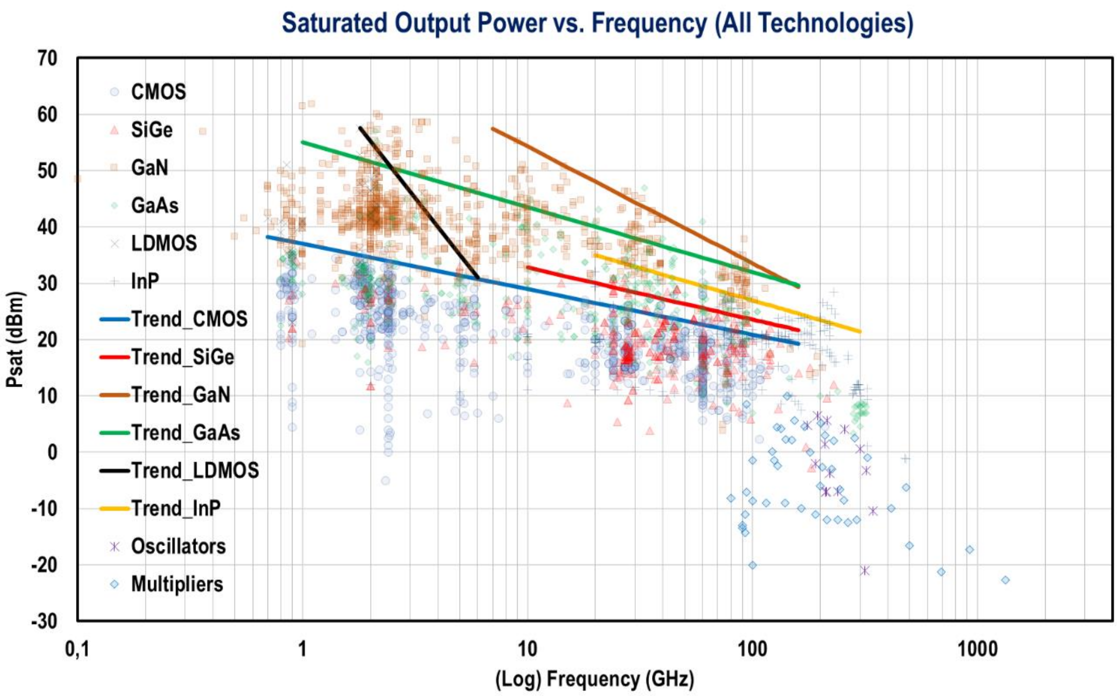


Figure 3-6: Saturated output power with trendlines for different technologies according to [WHM+21].

As the topic of power delivery is of utmost importance, we should assess different technology options as well. Therefore specific plots will be also shown from three technologies namely: CMOS, SiGe BiCMOS, and InP in Figure 3-7, Figure 3-8, and Figure 3-9, respectively. CMOS is selected due to its compatibility with mainstream digital signal processing and if things can be done in RF using CMOS, the other technologies will also be done due to this reason. However, it is also the slowest of the presented technologies in practical RF solutions and therefore SiGe BiCMOS has a major role in mmW commercial applications. Both technologies have shown commercial capability in different applications below 100 GHz. However, SiGe BiCMOS has more potential when going higher in frequency. It is well known fact that III-V semiconductors instead of silicon based can provide faster transistors and they have excellent properties in terms of power delivery than is utilized in power amplifiers for example for base stations. As InP is one of the fastest choices based on the recent publications shown in Figure 3-6, it has been brought as a reference. Its major challenge is compatibility with high-speed digital i.e. CMOS technologies. To address that research on heterogeneous integration and packaging is also on-going now. That path should be followed when 6G is considered as it may give opportunities to have higher output power and high-speed digital processing integrated at least into the same package. These choices in this report are not to exclude any other viable options and that is an area where we will see quite some competition between technologies and architectures in the future.

If we look the best performance reported in Figure 3-7, Figure 3-8, and Figure 3-9 around 200 GHz for these three technologies we will see roughly 5, 12 and 24 dBm saturate output power for CMOS, SiGe BiCMOS and InP, respectively. In addition to back off and other constraints the technology choice will have a major impact on how we can and should design antennas and antenna arrays if we will target for the same communications range. Picking one or the other will have also impact on power consumption, mechanics, heat, etc. Therefore, systems scenarios require many options for analysis not only due to use cases but also due to technology options.

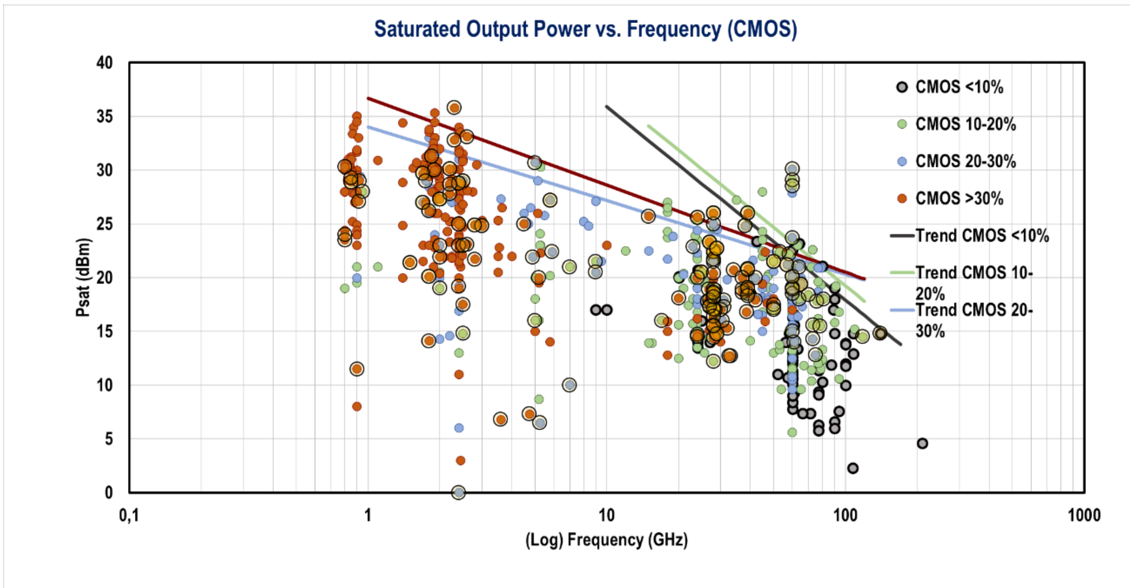


Figure 3-7: Saturated output power of CMOS based PAs according to [WHM+21]. The percentage number in the legend indicate power added efficiencies of the PA.

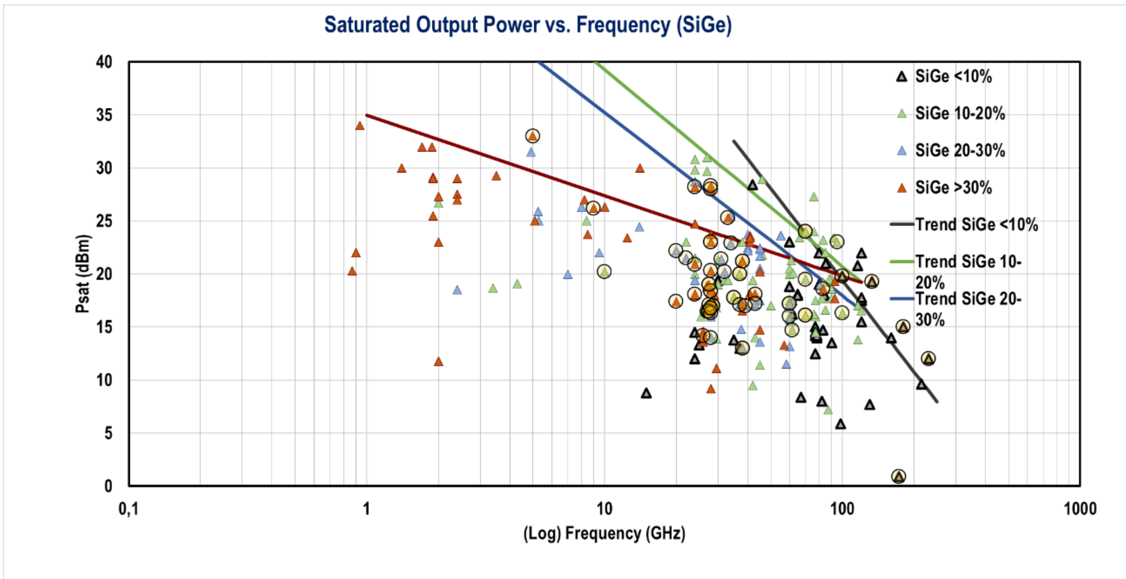


Figure 3-8: Saturated output power of SiGe BiCMOS-based PAs according to [WHM+21]. The percentage number in the legend indicate power added efficiencies of the PA.

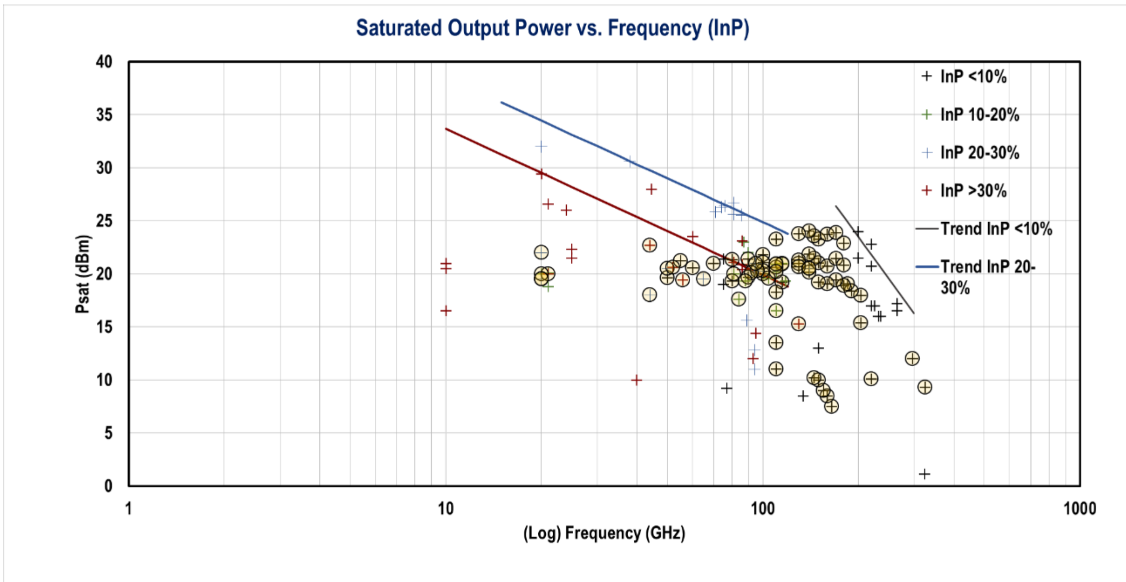


Figure 3-9: Saturated output power of InP-based PAs according to [WHM+21]. The percentage number in the legend indicate power added efficiencies of the PA.

3.3.2 Receiver Noise

Like any other electronic devices, all receivers add residual noises to the signals they receive, which consequently degrades the signal quality in terms of e.g., SNR. In this sub-section we discuss this noise-related HW impairment, focusing on the analogue part of a receiver.

Both active components (e.g. LNA) and passive elements (e.g. filter) in a receiver contribute to Rx noise, though in a different manner. A simplified, generic Rx architecture may well look like what Figure 3-10 shows.

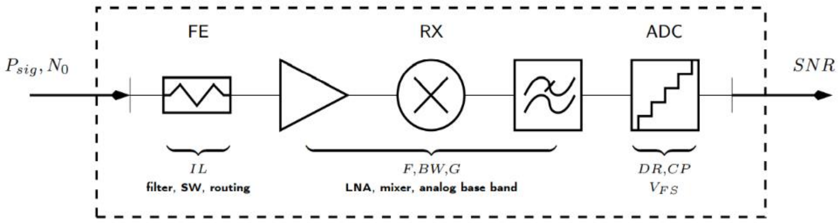


Figure 3-10: Simplified general receiver architecture.

For such a Rx chain with cascade stages as shown above, the so-called noise factor, F, which describes the degradation of SNR, can be written as (according to Frii's formula):

$$F_{tot} = IL_{FE} \cdot \left(F_{LNA} + \frac{F_{rest}-1}{G_{LNA}}\right). \quad (3\text{-}8)$$

The insertion loss IL_{FE} includes attenuations from all Front-End (FE) passive components between the Rx antenna port and the LNA input port. Typical examples of the passives are duplex filters (FDD), RF switches (TDD), routing and interconnect such as waveguide, cables, on-board transmission lines, etc. F_{LNA} and F_{rest} are the noise factor of the LNA and the whole rest part of the Rx after the LNA, respectively. And finally, G_{LNA} is the power gain of the LNA. As can be seen from the Frii's formula, Rx noise is dominated by the FE passives and the first active component LNA. The impact from the rest of the receiver is down-scaled by a factor that equals to the LNA gain.

In context of Rx noise, there are several fundamental HW challenges at mmW and THz frequencies. First, the insertion loss of passive components increases with frequency, resulting in a large IL_{FE} which contributes directly to the total Rx noise factor without any down-scaling factor. For this reason, integration becomes more critical for upper mmW frequencies than for frequencies below 100 GHz. To minimize the losses of interconnect and routing, IC packaging based on eWLB or embedded-chip solution and Antenna in Package (AiP) will play a key role in 6G system development. Second, the LNA noise factor, which also contribute to the total noise factor directly, increases rapidly as well with frequency at mmW range. As an example, Figure 3-11 plots the noise figure (logarithmic expression of the noise factor) of CMOS LNAs against the centre operation frequency [BEL20]. Apparently, the noise figure increases faster above 20 GHz and is more CMOS node dependent. Third, to support 100 – 1000 Gbps data rate, it is inevitable to apply wide bandwidth on order of 10s of GHz. As total noise power is proportional to bandwidth, the SNR will decrease by 3 dB for every doubling of the bandwidth. Overall, these challenging HW issues induce substantial degradation in the SNR, which degrades the Rx sensitivity and limits the usage of spectrum-efficient high-order modulations schemes and/or the range of the wireless links in 6G communications.

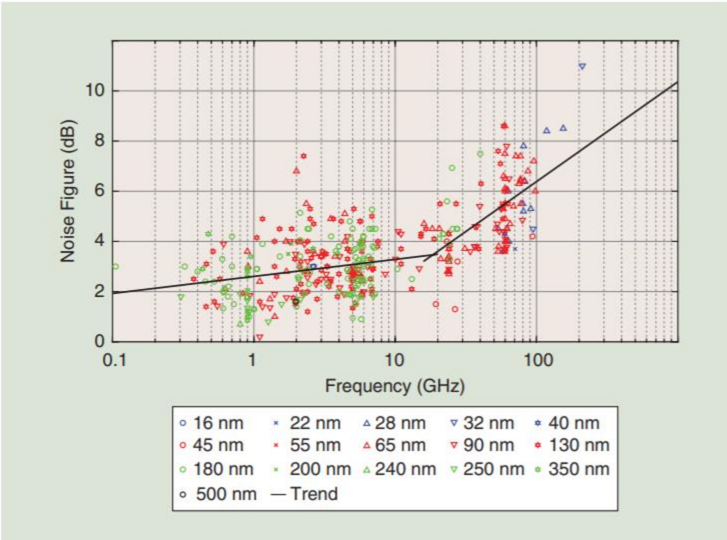


Figure 3-11: CMOS LNA noise figure vs centre frequency [BEL20]. The trend line slope is apparently larger for frequencies above 20 GHz.

The noise figure of the dominant active component, LNA, depends primarily on circuit design, the on-chip passive elements, and the transistor technology in use. While the passive influence is always significant, especially at lower frequencies, the LNA noise figure at mmW and THz is mainly determined by the used semiconductor devices. Figure 3-12 shows the noise figure of the integrated LNA circuits as function of the operation frequency for several commonly used semiconductor technologies. As can be seen, the noise figure values achieved by CMOS and SiGe LNAs are very spreading for a given frequency. This is probably due to the relatively large number of Si-based technology nodes and the divers design optimizations targeting for a broad and variety of use cases in wireless applications. For technology comparison, Figure 3-12 reveals the limitations of CMOS and SiGe about noise performance. In general, III-V based transistors (GaAs, InP and GaN) deliver lower noise figure than CMOS and SiGe, with GaAs as the superior (exponential trend line in Figure 3-12). Interesting to note is that more and more GaN-based LNAs were reported in recent years at frequencies approaching 100 GHz and even beyond. Roughly speaking, for commercial applications over 100 – 200 GHz, 3-5 dB noise figure can be expected for GaAs LNAs and 5 – 8 dB for SiGe LNAs.

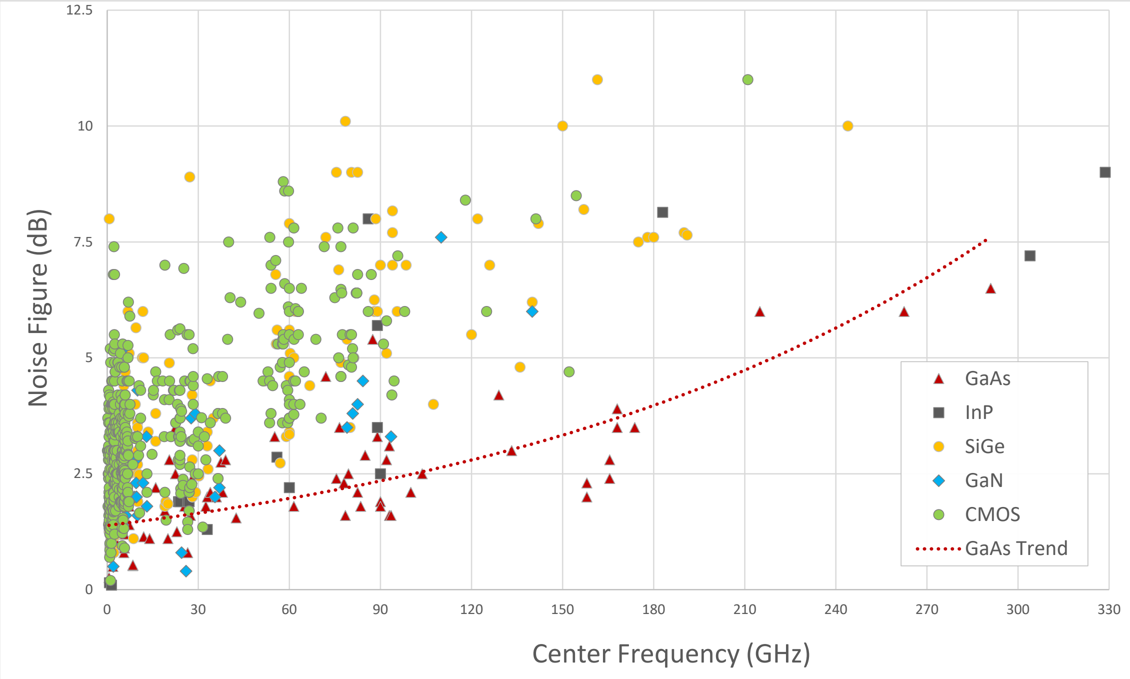


Figure 3-12: LNA noise figure vs centre operation frequency for commonly used semiconductor technologies (plotted based on a data sheet provided by [BEL21]).

3.3.3 Phase Noise

As a hardware impairment, phase noise causes significant degradation in the performance of high data-rate digital communication systems. The effects of phase noise highly depend on waveform, bandwidth, and oscillator source selection. In phase-modulated transmission systems, phase noise directly causes random rotation of received signal constellations and limits available bandwidth. Besides, phase noise may lead to adjacent channel interference in frequency division multiplexing systems. With increasing modulation bandwidth, a higher amount of phase error is accumulated. In this case, the influence of phase noise on the system performance grows, which cannot be compensated by increasing SNR [AK15].

For generating high frequency carriers, it is common to multiply a low-frequency oscillator to mmW frequencies due to speed limitation of oscillator, which results in higher phase noise level. Typically, one can assume that for each doubling of the frequency, the phase-noise level is increased by 6 dB. At lower signal bandwidth (<250 MHz), the system impact of the phase-noise is often determined by how well a transceiver can compensate for the correlated part of the phase noise. At higher bandwidth, noise-floor of the phase noise spectrum can become the dominant part [DPS20].

A critical component for 6G communication systems is oscillators with low phase noise, allowing for spectrum-efficient waveforms to be utilized. The state-of-the-art oscillators based on different semiconductor technologies operating at frequencies above 100 GHz are summarized in the following table. Equivalently, all these oscillators achieved a phase noise level of less than -70 dBc/Hz at/after being converted to 1 MHz offset frequency.

Table 3-5: VCO performance review in the frequency range 100 – 500 GHz.

Reference	Technology	Circuit	Frequency (GHz)	Peak Pout (dBm)	Phase noise (dBc/Hz)	Noise floor (dBc/Hz)
[VSW+20]	130 nm SiGe HBT	Fund. VCO	111 – 127	7.1	-90 -75*	--

[KLK+20]	40 nm CMOS	Injection-Locked Frequency Tripler Chain	120	3.0	-99.4*	-99.4
[VDT+13]	120 nm SiGe HBT	Fund. VCO	218 – 245	-3.6	-98**	--
[VDT+13]	120 nm SiGe HBT	VCO+doubler	288 – 311	-1.7	-101.6**	--
[VDT+13]	120 nm SiGe HBT	Push-push VCO	309 – 330	-13.3	-78**	--
[GZP13]	65 nm CMOS	Triple-push Oscillator	288	-1.5	-87*	-98.5
[YYK+14]	250 nm InP HBT	Fund. VCO	305.8	5.3	-116.5**	-120
[LBD+20]	130 nm SiGe HBT	VCO+PA+Doubler+PA+Doubler	307.4 – 321.3	-3.3	-90*	-122.8
[KSA+13]	250 nm InP HBT	QVCO	325	-5	-90.4**	--
[JM20]	65 nm CMOS	Coupled Harmonic Oscillator	438 – 479	-1.8	-100.6**	--

* phase noise at 1 MHz

**phase noise at 10 MHz

3.3.4 Data Converters

For higher data rates both bandwidth and resolution will play a major role in terms of feasibility as well as power consumption. Already 5G NR bandwidths from 100 MHz up to 800 MHz will have impact on transceiver power consumption changing the balance between PA, rest of the RF/analogue and digital conversion. Therefore, different approaches to limit the number of bits and oversampling the signal heavily have been proposed recently. However, to estimate those alternatives in detail some guidelines for system design are needed. Here, focus is mostly on ADCs because it is expected that the DACs are somewhat easier to implement and they are not similarly a bottleneck. Of course, in the uplink between a battery-constrained mobile device and a base station this may not be valid, but their PA is likely an even bigger challenge. Another challenge in DAC modelling is that the power consumption is more related to the analogue load and other features and key KPIs cannot be considered independent of the rest of the transmitter. However, some comments along the ADC discussion will be given.

From system perspective ADCs need to be dimensioned based on the receiver architecture. In narrowband channels/systems[8], ADCs may provide overly wide bandwidth because final channel filtering in frequency domain consumes less power and area in digital domain. But for channel bandwidths of multiple GHz or even tens of GHz this is not the case anymore. Feasibility and power consumption are promoting preference for analogue or hybrid signal processing and we will focus here only on receiving frequency channels that we would like to digitize for reception with minimum possible sampling rate and resolution. A conventional procedure to define ADC is as follows:

[8] In this context all cellular systems up to LTE having only one Component Carrier (CC) can be considered as such in mobile devices. However, base stations supporting multiple channels (one band at a time) the situation is already different. Concept of wideband vs. narrowband is always relative with respect to technology and in case of RF also to carrier frequency.

- The baseband bandwidth that is in the I/Q domain half of the RF bandwidth, which is oversampled in the ADC
  - 4x oversampling is needed for a typical digital synchronization
  - 2x is a fundamental minimum to avoid aliasing
- Receiver noise should be dominated by the receiver noise figure and not quantization noise of the ADC:
  - Therefore, 10 – 15 dB must be added on the top of the minimum SNR.
  - For example, for a signal with minimum SNR of 24 dB this means ADC dynamic range of at least 34 – 39 dB.
- ADC clipping/overshoot is highly non-linear function and is quite like digital clipping:
  - Therefore, ADC that has additional dynamic range which is at least as large as digital clipping margin or even somewhat better is needed.
  - This is quite close to the backoff of the signal i.e. depending on the modulation 3 – 10 dB additional SNR is required.
- In mobile devices receiving signal from a single source, analogue automatic gain control may reduce the dynamic range of the ADC effectively:
  - Typically, 6 – 12 dB is reserved for gain control purposes, and fine tuning of the signal level i.e. gain can be performed in the digital domain.
- In base stations, the near-far problem i.e. location of different mobile or stationary devices that cannot be solved by mobile transmit power control needs to be managed in case of multi-channel ADC in digital domain. Dynamic range between minimum and maximum received power over all channels need to be added to this number.
  - As extremely wide bands are considered one can assume that in transmit side power control limits the need to extend dynamic range of the ADC only by 6 – 12 dB.

Based on above the number of bits needed in ADC is in the range of 49 – 72 dB corresponding to 8 – 12 bits. These are typical or somewhat lower numbers than those used in current mobile devices and base stations. If we try to reduce these trade-offs, it needs to be done with spectrum efficiency, clock rate and analogue processing and accuracy. If with proper modulation and coding SNR requirement is only in the range of 16 dB and we manage to make excellent gain control either in transmit or receive side with need of only 3 dB gain control window for all dynamic operations and mobility then we end up to 38 dB dynamic range i.e. 6 bits. For 100 Gbps or Tbps communications that would mean even broader BW. Based on earlier analysis this is close to 16-QAM requirement with 30 GHz bandwidth for 100 Gbps and with an 8 – 10 bit ADC we can support theoretically the same with 20 GHz bandwidth. This would mean ADC clock rates of 40 – 60 GSps or increased parallelism of ADCs channelized using for example Component Carriers (CC) based on frequency.

As a note, 1-bit in resolution can be typically replaced with 2x oversampling. In case of 6 bits and 60 GSps this will lead to clock rate exceeding 1 TSps for a 1-bit converter. With an almost perfect analogue gain control in transmit and receive ends this might be theoretically possible but sampling rates in the range of that sound highly challenging even if parallelised heavily.

Similar, to the power amplifier case, a comprehensive survey on ADC performance is available over 20 years' time span in [MUR21]. This is the most well-known reference for the academic literature in this field. Comparison to some commercial ADCs with packaging and all necessary interfaces for independent operation these estimates are rather optimistic. The survey gives formula for Walden's figure-of-merit typically used to evaluate ADC performances of different bits and sampling rates to each other as

$$FOM_W = \frac{P_{ADC}}{2^{ENOB}.f_s}, \tag{3-9}$$

where P_{ADC} is ADC power consumption, ENOB is the effective number of bits[9] and f_s is the sampling rate. Figure 3-13 shows the Walden FOM as a function of ADC Nyquist rate that is a better measure for sampling as it takes care of the actual effective signal bandwidth also for oversampling converters. It is clearly shown that when signal bandwidth goes above certain bandwidth power consumption starts to increase as a function of frequency in an unfavourable manner.

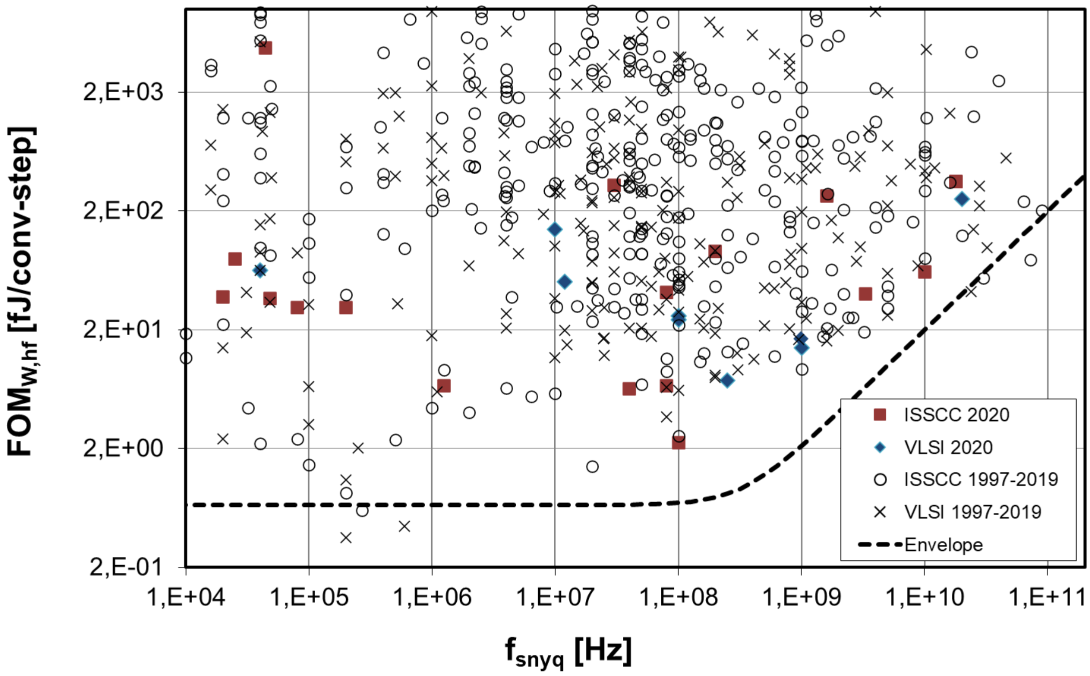


Figure 3-13: Walden FOM of published ADC design versus Nyquist sampling rate according to [MUR21].

If we analyse further the data from the survey and calculate dynamic range i.e. SNDR and power consumption of the ADCs, more practical numbers can be observed for system analysis. Figure 3-14 shows samples and trends. For comparison, some commercial high-speed and high-resolution ADCs have been added based on the public data sheets available in the internet. Those are marked as REF and REF2 in the plot. There are some examples that can go up to 10s of GHz signal bandwidth but at the cost of rapidly increasing power consumption. If we look at state-of-the-art academic and commercial ADCs their trend in terms of resolution is quite similar (blue trend line) but there is a significant difference in power consumption (red trend lines). It is visible that an individual ADC can consume 1 W or even more in practical systems and due to large variation in implementations precise estimates are difficult in absolute scale. However, trends are evident and need to be taken carefully into account in system analysis.

[9] ENOB is always lower than theoretical number of bits due to quantization due to noise and jitter. This number is also the one that is needed in system analysis.

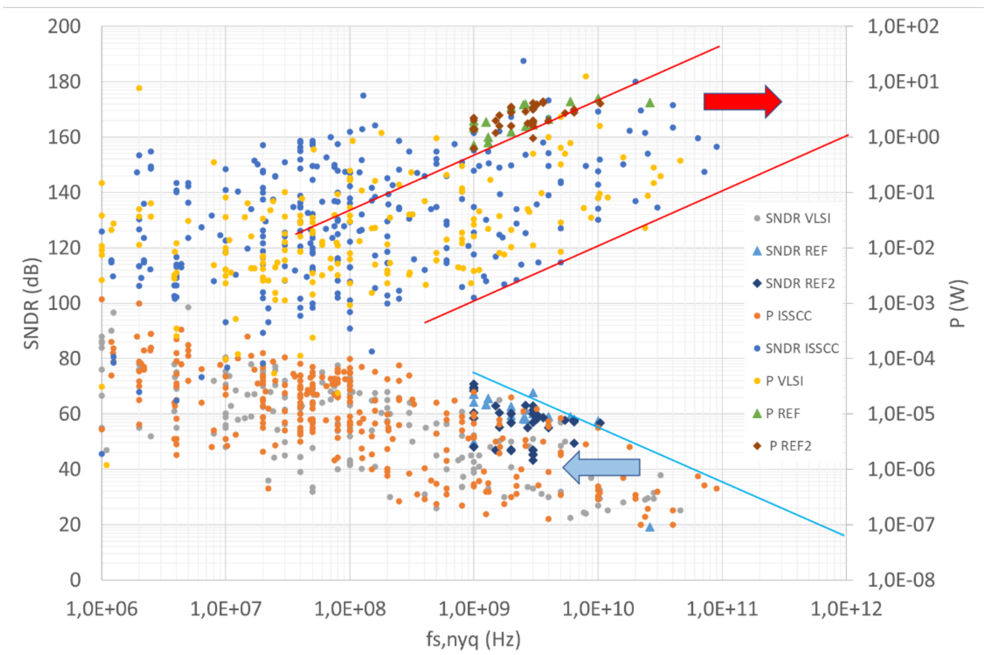


Figure 3-14: SNDR and power consumption of ADCs as a function of bandwidth based on data from [MUR21] and commercial data sheets.

3.3.5 Digital Signal Processing

With the increase of bandwidth and data rate, the power consumption of the Digital Signal Processing (DSP) becomes significant. Therefore, it is required to consider the trade-off between the energy consumption and performance in the evaluation of the signal processing algorithms.

The DSP model for a single link is illustrated in Figure 3-15. At the transmitter, the input data frame $\boldsymbol{b}$ of length N_{fb} bits is mapped to complex samples vector $\boldsymbol{x}$ of length N_{fs} samples using a function $\boldsymbol{x} = f_{tx}(\boldsymbol{b})$. The effective channel represents the transfer function $f_h(\cdot)$ between the output $\boldsymbol{x}$ of the DSP at the transmitter and the input $\mathbf{y}$ of the DSP at the receiver, such that $\boldsymbol{y} = f_h(\boldsymbol{x})$. This function summarizes the wireless channel, hardware impairments, synchronization error in addition to the additive noise. The DSP at the receiver aims at decoding the data correctly such that $\hat{\boldsymbol{b}} = f_{rx}(\boldsymbol{y})$.

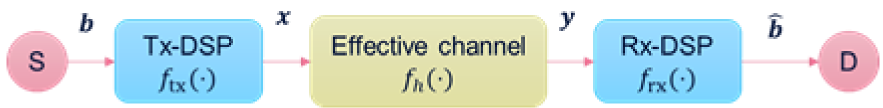


Figure 3-15: Digital signal processing model.

For the signal flow, the DSP design needs to be fast enough to consume frames with a speed larger or equal to the frame rate. Moreover, the processing latency, i.e. the time difference between consuming the last input sample and producing the first output sample, should be smaller or equal to a certain threshold, which is determined from the E2E latency budget.

The reliability requirements defined by a Frame Error Rate (FER) threshold is the main KPI that needs to be considered in the evaluation of the DSP algorithm design. There is a trade-off between complexity and reliability, which needs to be considered to optimize the processing architecture for energy efficiency. The architecture complexity is determined by the number of arithmetic operations and memory access required at each frame. In addition, the operations precision determines the size of the required logical and memory resources, which influences the energy consumption [SDM+20]. Decreasing the resolution of the operations reduces the complexity but may lead to signal distortion and thus degrades the reliability.

The DSP requirements at the base station scales with the number of spatially multiplexed users, i.e. with the number of transceiver chains.

3.3.6 Antenna Approaches (Phased Array vs Lenses)

At frequencies above 100 GHz the questions related to packaging and the location of antennas are of high importance. Different aspects are discussed for example in [PAB+20] and [NKU19]. From electronics perspective the relative size compared to the active circuitry matters a lot. At lower mmW region in 5G NR, antennas are still large compared to the highly integrated RF transceivers and therefore single IC is typically driving four antenna elements [KSR17], [VAL18] and in case of dual-polarized antennas four dual-feed elements. This enables implementation of large arrays containing multiple IC's and antennas as part of the same RF controlled phased array [SHS+19]. However, if more transmit power is needed than what could be available from CMOS or SiGe BiCMOS chips, external PA would be required. Using an PA outside the transceiver RFIC would take a much larger area than the antenna, thus the limiting supported antenna configurations. Matching form factor of the electronics and the antenna matrix becomes a major constraint that limits the practical size of the antenna array even further [LDK+18]. This also makes mechanics and thermal design much more complex, which has limited the high output power PA technology usability already at 28 GHz range. When frequency gets higher the issues will become apparent also when integrated antenna elements are being adopted on the same chip with RF circuitry, for example at frequencies above 200 GHz [RGH20].

Therefore, the question is not only on the antenna element performance in classical sense but its form factor and impact to the rest of the system including transmitted power and power amplifier performance [WAF21]. Antennas can be implemented on many different techniques. Radiators integrated on the same chip with the transceiver could be an alternative for external radiators implemented on Printer Circuit Board (PCB) or using some other technology like printed circuits. In all cases, the interface and packaging with the transceiver IC will become even more problematic when frequency increases.

As indicated earlier for decent range we need even larger antenna gain at 100 - 300 GHz than in 5G NR FR2 bands due to lower output power capability of PAs, higher noise of receivers and larger loss in the radio channel for unity gain antenna element. In transmit and receive ends this means the use of either highly directive antenna (horn, lens, etc.), like in [RGH20] or a very large antenna array that is substantially scaled up in terms of elements i.e. RF parallelism from 28 GHz. Theoretically the latter sounds attractive but causes a lot of practical challenges. On the other hand, highly directive antennas are very different in terms of steering properties. Switchable steering has been proposed [AAK16] where additional benefit can be achieved by multiplying PA power by the number of parallel elements.

To evaluate total link level antenna gain available from an ideal antenna array for different scenarios i.e. number of antennas at the other end of the link are shown in Figure 3-16. In case of antenna arrays individual antenna elements can provide a small positive gain but in most cases that is in the range of 0 – 5 dBi per antenna and interconnect. Therefore, the gain scales up only 10 dB or much less for the whole link even in the best case. As the link level gain requirement can be much more than 50 dB even for the link of 10 m at 300 GHz [RKL+20] it can lead to unreasonable number of antennas at longer link ranges. 100 dB total gain would require 100,000 antennas at both ends of the link. Such scale of parallelism has not seen or implemented even close in any HW implementation in the literature. Very likely it will not be a realistic choice for 6G at least in the considered 10 year time scale. Therefore, at least for the longest links, directive antennas over arrays need to be considered. Directive antennas are in fact the de facto for present static links e.g. in radio backhauls at lower frequencies, as well. Analysis for compromises between link range, data rate, power consumption, cost and complexity need to be carried out carefully. This is one of the major challenges for HW aware designs as one model will not fit well to all use scenarios with respect to antenna/RF transceiver interface.

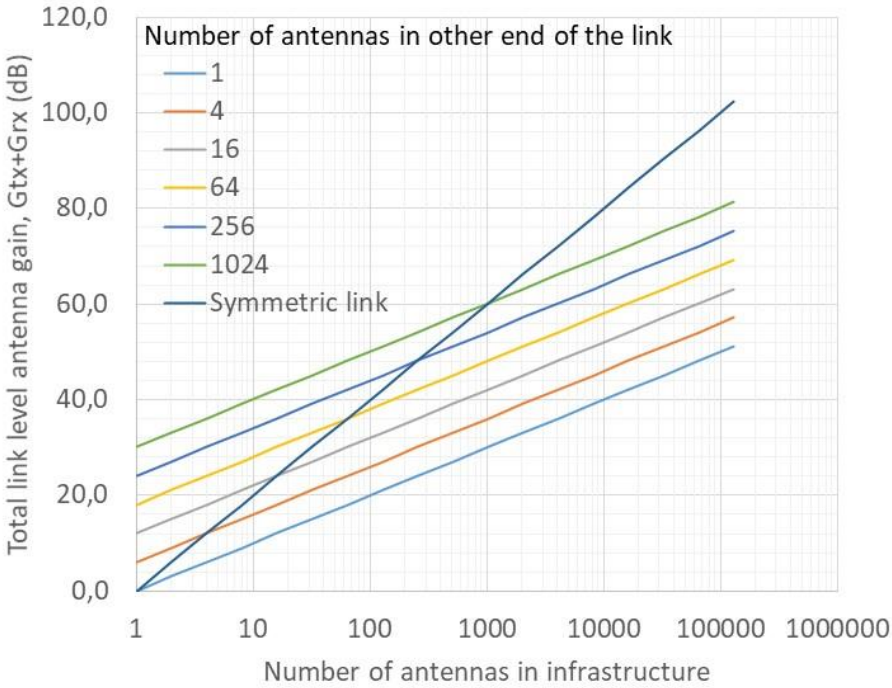


Figure 3-16: Combined antenna gain at both ends of the link for an ideal antenna array (unity gain antenna elements) as a function of number of antennas (logarithmic scale) in the infrastructure side. Different curves present the number of antennas at the other end of the link (mobile, backhaul etc.).

To highlight form factor (i.e. physical dimension) aspects Figure 3-17 shows a relation between the carrier frequency and the typical antenna ($\lambda/2$). At the upper mmW range, the distance between elements ranges between 500 – 1500 µm. The maximum area available for a single antenna element and the associated electronics as part of a transceiver is only 0.25 – 2.25 mm^2 per RF path. As a typical RF front-end for an mmW range transceiver is roughly in the order of 1 mm^2 with on-chip power limited PA. There is a major transition in the relative size of antennas and electronics over the upper mmW frequency range even if without any discrete PA, which may provide additional transmit power. The physical size of the electronics is one essential aspect to be considered when circuit architecture, packaging concept etc are designed. Antenna arrays will be impacted by many implementation non-idealities like coupling between antenna elements leading to limited isolation between polarizations, which will have effect on the performance of the electronics. Therefore, co-optimization of antennas with the RF electronics of the transceivers is not straightforward, but essential to achieve for the best RF performance.

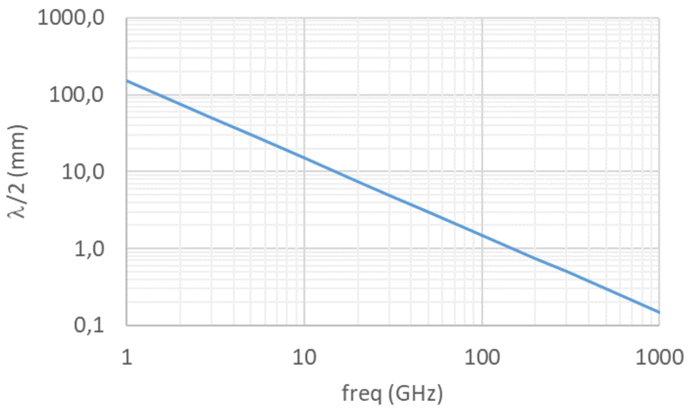


Figure 3-17: Typical antenna element distance (λ/2) in a phase array in mm as a function of frequency in GHz.

Finally, some quick comments are given on reflective surfaces and feasibility of controllable reflective surfaces also known as Reconfigurable Intelligent Surfaces (RIS). Those are under intense research including both communication, metamaterial, and electronics aspects [HZD+20], [RZD+20], [PTL21]. The general idea is to enhance link range by steering and focusing the transmitted signal i.e. beam to the right target. This additional beam steering device should focus the energy from a larger surface to the target nearby. This will be a complex lens system and transitions of signals from far field to near field. In system level this would require distributed beam control over multiple devices which is a simple control task for mobile objects. Feasibility or usability in time frame of 6G will be seen only later. There are many EU projects studying various aspects of RIS including REINDEER, RISE-6G and ARIADNE. Of course, reflections from any environment are only usable if the beams from different sources are strong enough to be detected as in case of 5G. However, these aspects are part of the radio channel studies.

3.3.7 Transceiver Architecture Options

The main building blocks of the 6G radio Transmitter (Tx) and Receiver (Rx) are shown in Figure 3-18 and Figure 3-19, respectively. It can be seen from the block diagrams that the future 6G extreme data rate radios will require parallelism in both Tx and Rx, and the parallelism can be implemented in different ways to overcome different implementation or spectrum allocation challenges. The 5G mmW radios utilize antenna arrays at both ends of the radio link to improve the system coverage. The current 5G antenna arrays are parallel radio implementations, and the key findings and learning of implementations of those will be considered when 6G radios are designed.

The main functionalities of the radio transceiver are waveform generation, analogue-digital conversions, frequency up- and down conversions, signal amplifications, and signal radiation through the antenna. The number of converters and signal paths inside of the transceiver depends on frequency allocations of the operational frequencies of the RF band, technologies of the used converters, and relative signal bandwidth compared to the operational frequency. Among physical constraints, a very typical and natural relative bandwidth for RF front-ends is in the range of 10% [10]. If wider or narrower bandwidth is required, the design gets more complex and/or costly. Therefore, bandwidths up to ~10 % can be considered as narrowband and above as wideband.

[10] Relative bandwidth is defined in BW/f_c where BW is the required RF bandwidth of the signal and f_c is the carrier frequency or the center of the frequency band where the signal is transmitted in frequency dependent channelization schemes.

Relative bandwidths of 20 % could be possible but they will always negatively impact on the radio performance and cost, and those need to be analysed case-by-case with other design constraints. The signal bandwidth affects baseband signal processing performance (digital, mixed-signal, and analogue) and impacts RF and antenna performance, including beam steering capability.

The communication range impacts both the TX output power and the RX noise figure requirements, but they cannot fully solve the link budget challenge even at the low mmW range. Thus, the antenna gain, implemented with antenna arrays or highly directive antennas, such as lenses or horns, must be taken into account in the system analysis. Multiple Tx signal paths will be required to increase the radiated signal power since the available Tx power of individual power amplifiers is limited. Beam steering support is needed from 6G RF transceivers to increase coverage of the system since used Tx and Rx beams are narrow or a few degrees wide [RKL+20]. For the reasons mentioned above a generic reference model to describe any hybrid MIMO approach would require scalability of parallelism, as shown in Figure 3-18 and Figure 3-19, respectively.

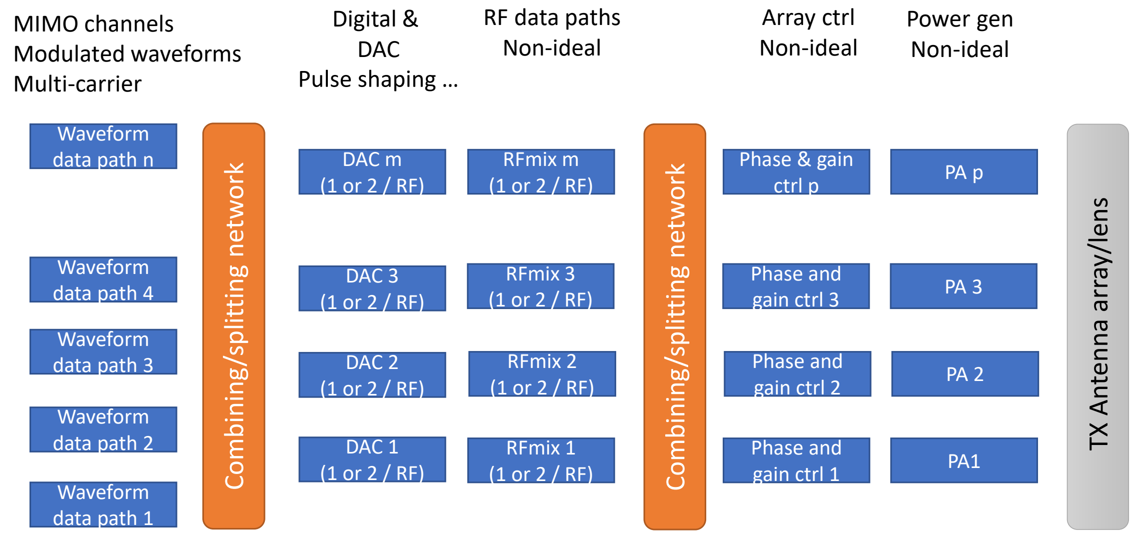


Figure 3-18: The main building blocks of potential concept 6G transmitter signal path. Signals flows from left to right but due to many theoretical configuration options detailed connections are not shown.

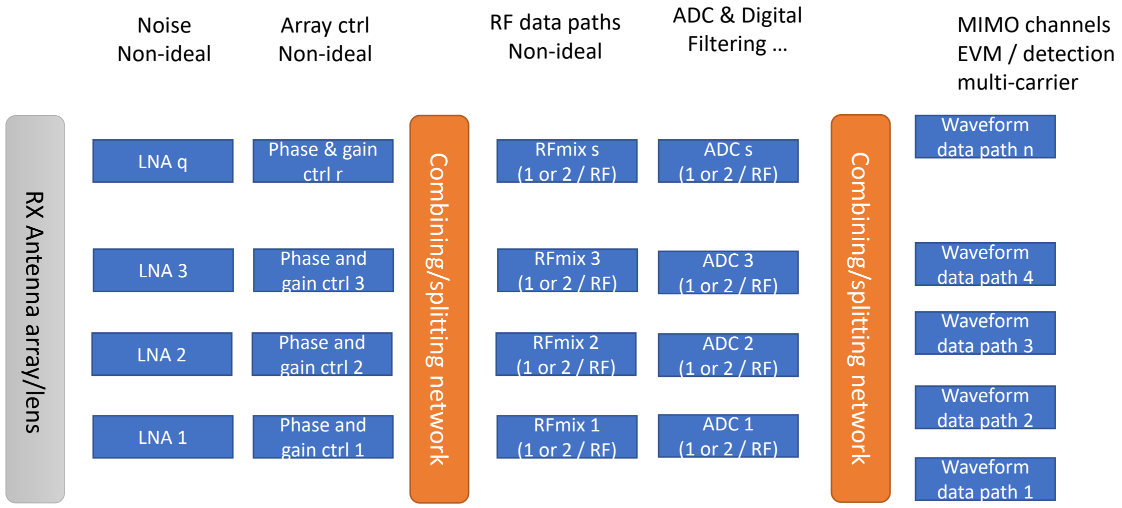


Figure 3-19: The main building blocks of potential concept 6G receiver signal path. Signals flows from left to right but due to many theoretical configuration options detailed connections are not shown.

A possible single frequency RF architecture of 6G transceiver with two frequency generation topologies is presented in Figure 3-20. The frequency generation of the LO can be done multiple ways depending on the selected RF frequency plan. A baseband or a low Intermediate Frequency (IF) signals from the DSP unit in Rx and Tx are directly mixed to the final operational frequency in proposed RF architecture shown in Figure 3-20. This architecture[11] has a merit of enabling a simple RF frequency plan without image frequencies which are evident with superheterodyne RF architectures. The filtering of the image frequencies in the signal path requires RF filters, which are not easy to implement at 150 GHz or 300 GHz operational frequency bands. Additionally, if external filters are used, then the signal needs to be routed out and in from the RFIC, leading complex circuit implementation and increases the number of input/output pins and the chip area. However, depending on the Out Of Band (OOB) requirements, some RF filtering may be needed to comply regulatory requirements, but these need to be studied for each geographical area separately, since OOB regulatory requirements vary significantly between different regions.

Voltage Controlled Oscillator (VCO) in Figure 3-20 is used for LO generation to support frequency changes e.g., channelization within the band and typically in mobile devices also for Doppler shift compensation. The VCO may operate at carrier frequency or at lower frequency which is upconverted with multiplier stages. However, the multiplier stages (like frequency doublers) increase the phase noise of the VCO by 6 dB in each multiplication by two stage. Thus, a thorough analysis of the phase noise performance of different VCO approaches is needed to optimise the transceiver's performance. The final frequency VCO tuning range’s slope, monotony, and tuning accuracy of the VCO will be more challenging when the operational frequency of the VCO increases.

The TDD radio architecture enables much more simplified RF front-end implementation compared with the FDD or in-band full duplex radio. The Tx and Rx are operating at different time instances in TDD system and typically Tx and Rx are sharing the same frequency channel for the operation as in LTE TDD and 5G TDD systems. In FDD or in-band full duplex systems, the Tx and Rx operate typically or always simultaneously, and this operation leads to use of a duplex filter with a shared antenna. The transceiver functionality in the TDD radio can be implemented with a RF switch or RF circulator to connect the Tx or the Rx signal to the shared antenna, while in the FDD radio a duplex filter is required. The 6G radio may use multiple antennas to enhance the radiated radio performance. The antennas may form an array to support beam forming and steering and additionally external focusing antenna may be used to focus the radio beam even further. Lens antenna arrangements can be used for the focusing antennas. The whole antenna arrangement including first antenna radiators and focusing antennas need to be co-design since physical dimensions and relative positions of those have significant effect to the total radiated antenna performance.

[11] It is essential to avoid additional interference signals with wideband transceivers and both direct conversion (DiCo) or low-IF are providing this option.

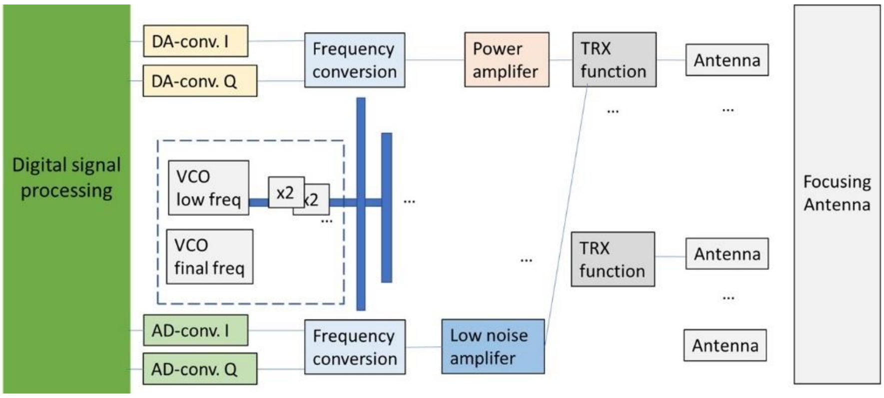


Figure 3-20: Possible one frequency conversion 6G transceiver architecture.

Only one Tx and Rx signal path is shown in Figure 3-20 to simplify illustration of the block diagram. Actual implementation of the 6G transceiver will be more complex due to parallel signal paths.

3.3.8 Classifying HW Against Different Requirements

No foreseen radio solution can scale with a reasonable cost and power consumption to any possible bandwidth, frequency, and duty cycle. Thus, application-specific radios will be implemented in the 6G era. It is expected that the new 6G radios complement and reuse the existing 2G to 5G in cellular network infrastructures. If there is a radio that can support the selected use-case, there is no need to design a new one. Therefore, most use cases are expected to be implemented with radios supporting previous standard generations up to 5G. Therefore, the focus here is on extremely high data rate applications in most cases. However, forthcoming 6G radios can be considered both for infrastructure, end user, radio relay and device-to-device communications. Sensing and positioning capability is an additional aspect that brings new features to the discussion. Releases of 5G NR standard are already and will bring new means for this before 6G standardization. Those aspects are considered mostly in deliverables of WP3 in this project.

To select the most suitable radio for each application and focus on the use cases that truly require new radio technologies, radios for communications and sensing can be categorized coarsely by purpose as follows

Communications:

- low/mid/high data rate.
- short/medium/long range.
- other properties, like latency.

Sensing and positioning:

- precision.
- range.

etc.

One device can support one or more of these purposes. Therefore, the other major classification needs to be done against different device types including radios both in infrastructure and end user device. The list below shows one possible way to categorize the device types.

Device classes

- Infrastructure backhauls.
- Infrastructure base station.
- Mobile device extreme data rates/very high precision sensing.

- Mobile device handheld.
- Mobile/static device IoT low data rate (long range short range).
- Mobile/static device IoT high data rate.
- Device to device (D2D) high data rate – short range (data centres, etc.).

In this phase only a short introductory classification will be done as the baseline for further studies as given in Table 3-6. Before use cases will be defined with details coarse guideline is sufficient to alleviate the fact that one device will not fit for all purposes and in 6G we will likely see multi-standard, multi-band, complex radio devices with even increased scaling for new targets. It can be seen from the Table 3-6, that there are some commonalities between device classes enabling the radio solutions usage in multiple devices. However, each device class has its own drivers and use cases, which may lead to a customized radio solution in the final product.

Table 3-6: Coarse classification of devices based on radio properties/capabilities.

	mobility	**beam steering angle**	**beam width**	**TX power**
Infrastructure backhaul	No	Low	Wide	High
Infrastructure base station	No	Moderate	Wide	High
Mobile device extreme data rates/very high precision sensing	Low	High	Mid	Mid
Mobile device handheld	Moderate	High	Narrow	Mid
Mobile/static device IoT low data rate (long range short range)	High	High	Narrow	High
Mobile/static device IoT large data rate	Moderate	Moderate	Mid	Mid
D2D huge data rate – short range (data centres, etc.)	No	Low	High	Low

3.3.9 Conclusion of HW Gaps

Technologies and architectures to implement HW for extremely high data rate radios is among the biggest challenges on the way towards 6G. High data rate and high precision sensing require wide bandwidths that are available only at carrier frequencies above 100 GHz. The physical limits of semiconductor technologies, packaging etc. are approaching faster than before and must be considered more carefully compare to the way it was considered after the first steps of 2G with big and bulky radios. Moore’s law will not give similar benefits automatically as earlier and RF technologies reach their boundaries resulting lower output power and higher noise per device when frequency increases. Therefore, there are no simple or obvious solutions that can be taken as it even from 5G NR FR2 considerations. New architectures and tradeoffs in conventional wireless communications system targets, like bandwidth efficiency, are likely needed for the best compromise.

Conclusion based on this is that considerations on 6G systems need to be very well aligned to key technology parameters to ensure economic and technological viability of 6G systems. Research activities in different fields are on-going and they will gradually give new opportunities and answer many essential questions ranging from the role of silicon vs. other technologies to viability of new applications. As the complexity is large one of the key aspects is to model and abstract technologies in a way that they could give reasonable predictions to optimize systems concept and KPI’s and KVI’s related to those.

In addition, availability of spectrum and rules to use it have major impact on the cost related to radio devices. Extremely large bandwidths can't be easily found from contiguous spectrum allocation. Therefore, there is a risk that spectrum use will be split similarly as in 4G and 5G to different aggregated bands. This is not a preferred solution from implementation perspective especially when technology boundaries will impact the HW implementation. This means also that the spectrum regulation considered in WP1 of this project will have impact in the future in addition to the feasibility aspects as discussed in this section.

3.4 Waveform related Gaps

Hardware-related constraints and requirements stemming from use cases will guide the choice of waveforms best suited for supporting the operation of B5G/6G systems. General worsening of hardware capability and quality with increasing operating frequency, operation with very narrow beams and use of large bandwidths result in a specific set of requirements that differs from requirements imposed on waveforms in 3-5G. This is not to say that legacy waveforms (such as CP-OFDM) will not be applicable in B5G/6G systems; however, it is of interest to look what the alternatives to CP-OFDM are. The details of this development are given in the following sections.

3.4.1 Fundamental Hardware-Related Limitations

As elaborated in detail in the section on PA power capabilities (Section 3.3.1), maximum transmit power will be limited in the upper mmW range (100 – 300 GHz). Furthermore, the negative impact of phase noise (Section 3.3.3) and thermal noise (Section 3.3.2) is expected to be significantly higher at higher frequencies. High requirements on data rate result in use of very large bandwidths (Section 3.2.1), which may result in increased frequency selectivity and hardware impairments related to wideband operation (such as nonlinear distortion with memory). Finally, maintaining the same effective antenna aperture as frequency scales implies that very narrow beams will be used, which will drastically reduce the number of users that need to be served simultaneously in different frequency resources. Waveforms chosen for operation in the upper mmW regime need to be designed with these fundamental limitations in mind. We note that some of the requirements that are more pronounced at upper mmW (such as need for coverage extension by careful waveform design) are also relevant for operation at lower frequencies (cf. the long-range fixed access Section 2.2.1).

3.4.2 Definition of Waveform KPIs and Relevance of Main KPIs in the B5G/6G Context

In conjunction with KPIs defined for different functions in Chapter 2, related waveform design KPIs can be identified. Waveform KPIs analysed in this contribution have previously been used in similar comparative studies of waveforms, cf. [ZLG+16]. It is also of interest to assess the relevance (high/medium/low) of selected waveform KPIs in the context of B5G/6G, specifically, in view of target technologies and hardware impairments (e.g. reliance on beamforming, employing GHz-scale bandwidths and use of upper mmW carrier frequencies), as well as target use cases. The relevance of KPIs in the context of B5G/6G often exhibits dependence on the choice of technology or other parameters, e.g. on carrier frequency. These cases will be identified and elaborated.

3.4.2.1 Main Waveform Design KPIs

- Power efficiency – importance: high
    - Maximum PA power scales down with carrier frequency (Section 3.3.1), which imposes severe limitations on coverage. Use of waveforms with limited/low envelope variations enables operation close to PA saturation point and achieving near-maximum output power from the PA, resulting in coverage increase.

- Spectral efficiency – importance: medium
    - There is currently an abundance of available bandwidth in the frequency range 100 – 300 GHz and designing waveforms for high spectral efficiency is generally not instrumental for achieving the projected high data rates. The importance of this depends, however, on the available bandwidth, and is more pronounced in sub-100 GHz frequency bands.
- Robustness to HW impairments (PA nonlinearity and phase noise) – importance: high
    - Phase noise levels increase with carrier frequency (Section 3.3.3) and use of extremely large bandwidths can lead to an increase in PA nonlinear distortion. Choosing waveforms that are robust to HW impairments is instrumental for reliable operation and increased coverage.
- Implementation complexity – importance: high
    - Keeping implementation complexity low is of importance for battery-driven user/mobile devices as well as infrastructure nodes since complexity is tightly connected to energy consumption and cost. This applies to digital baseband hardware, mixed-signal units (ADCs/DACs) but also to analogue RF hardware, where complexity issues are related to novel technologies which require more complicated packaging and power delivery structures. Complexity issues will also be exacerbated by use of GHz bandwidths. It is therefore of high importance to design waveforms towards low implementation complexity. It should be noted that often there exists a trade-off between the need for waveforms/waveform processing to provide robustness to HW impairments and implementation complexity (unless a waveform is inherently robust to HW impairments, e.g. constant-envelope waveforms exhibit no nonlinear distortion from the PA).
- Inherent and processing latency – importance: medium
    - Latency due to waveform pulse properties (poor time compactness due to time-frequency ambiguity) is not deemed to be an issue for B5G/6G due to the use of very large bandwidths which in turn give very short pulse durations. Waveform processing latency coming from DSP will likely also not be a big issue, and most of the latency in the system is expected to come from the network side, e.g. from employing Hybrid Automatic Repeat reQuest (HARQ).
- Compatibility with MIMO – importance: medium to low
    - At frequencies above 100 GHz, wireless channel, and system properties (number of antennas >> number of independent spatial directions) will likely decrease the importance of fully digital beamforming, and thus designing waveforms for ease of combining with MIMO will be of reduced importance. At frequencies <100 GHz there can still be room for applying MIMO [BEA19] and so MIMO compatibility should not be completely ignored in waveform design.
- Frequency resource allocation flexibility (multiuser) – importance: medium
    - In a system using analogue beamforming with very narrow beams the likelihood of several users using the same beam will be low. For this particular use case, there is little interest in making waveforms compatible with flexible allocation of frequency resources to multiple users (as is the case with OFDM/OFDMA). In case wider beams are employed, and/or hybrid or fully digital beamforming is used, the importance of waveform compatible with FDMA grows.
- Robustness to time-selective channels – importance: medium
    - The impact of time variations in the wireless channel is more pronounced in upper mmW frequencies due to increase of Doppler spread/reduction of coherence time. However, a large part of B5G/6G use cases assumes low to no mobility (cf. Section 2), mostly due to difficulties related to beam management

  - with extremely narrow beams. One exception is the envisioned long-range connectivity scenarios with high speed (Section 2.2).
- Robustness to frequency-selective channels – importance: medium
  - Use of very narrow beams will likely contribute to a significant reduction of the frequency selectivity of the channel. In several use cases (especially ones assuming LOS propagation) the channel may reduce to a single tap. On the other hand, the use of extreme bandwidths would result in an increase of frequency selectivity. Impact of frequency selectivity and its importance for waveform design are therefore strongly dependent on the use case.
- Out of band reduction capability – importance: medium to high
  - Operation in frequency bands adjacent to bands that carry interference-sensitive traffic (such as satellite communication at 130 GHz band) might be subject to strict regulatory limitations on OOB radiation. Importance of controlling OOB radiation is also dependent on the region of application. On the other hand, use of extreme bandwidths and decreased criticality of high spectral efficiency enable a more prominent use of frequency guard bands which relaxes the need for waveform-design-related OOB suppression in some scenarios.
- Multiband operation capability (single user) – importance: medium to low
  - Challenges with simultaneous use of multiple bands in a single user-infrastructure link mostly come from the increased hardware complexity, and do not impose stringent design requirements on the waveform itself.
- Bandwidth scalability: medium to high
  - The possibility of adapting the waveform bandwidth to available bandwidth is important, not least in the scenarios where such bandwidth scaling is related to changes in coverage requirements.

3.4.2.2 Derivative KPIs

There are two important system KPIs that can be directly related to basic waveform KPIs presented in the previous section: coverage and energy efficiency. The connection between basic KPIs from Section 3.4.2.1 and these derivative KPIs is elaborated in the following.

3.4.2.2.1 Coverage

In [RKL+20], coverage was identified as a problematic aspect of operation at upper mmW frequencies. This is especially true in the uplink, and at the cell edge. Moreover, increasing coverage will also be important in long-range wireless access networks, especially the ones based on terrestrial access which will operate on sub-6 GHz frequencies. Therefore, coverage is a problem that is relevant in all frequency bands of operation.

A slight reformulation of main ideas from the section on range (Section 3.2.4) is given here for the ease of exposition; the reader may turn to the aforementioned section for the description of technical details.

Coverage can be quantified in several ways, all of them relating link quality with distance in some sense. To this end, SNR surplus (defined as the difference in dB of maximum achievable SNR, $SNR_{Rx,max}$ and SNR required to achieve a certain BER/BLER, SNR_{req}) can be observed as a function of the distance d between infrastructure and user nodes when other system parameters are fixed. Negative value of the surplus $SNR_{Rx,max} - SNR_{req}$ indicates that coverage cannot be achieved at distance d.

In a single link, line-of-sight scenario where transmitter and receiver are equipped with antenna arrays and where each antenna is fed by one PA, maximum achievable SNR, $SNR_{Rx,max}$ for the downlink of such a link can be formulated as

$$SNR_{Rx,max} = P_{PA,max} - OBO + G_{element,eff,Tx} + 20\,log_{10} N_{ant,Tx}$$
$$-20\,log_{10} \frac{4\pi df}{c} + 10\,log_{10} N_{ant,Rx} + G_{element,eff,Rx} - 10\,log_{10}(kTBF), \quad (3\text{-}10)$$

where

- $P_{PA,max}$ [dBW] is the maximum output power from the PA,
- OBO [dB] is the power backoff at PA output,
- $G_{element,eff,Tx}$ and $G_{element,eff,Rx}$ [dB] are the antenna gain of a single antenna element + antenna input losses at the transmitter and receiver, respectively,
- $N_{ant,Tx}$ and $N_{ant,Rx}$ are the number of antennas at the transmitter and receiver, respectively,
- d [m] is the distance from Tx to Rx,
- f [Hz] is the carrier frequency,
- c $[m/s]$ is the speed of light (3×10^8),
- k [J/K] is Boltzmann constant (1.38×10^{-23})
- T [K] is the temperature,
- B [Hz] is the bandwidth of the filter at the receiver (assumed equal to system bandwidth),
- F is the noise figure of the receiver.

On the other hand, SNR_{req} can be obtained from system bandwidth B and bitrate R by inverting Shannon's capacity formula for AWGN channel and adding an implementation factor ϕ_{impl}, as

$$SNR_{req} = 10\,log_{10}\left(2^{R/B} - 1\right) + \phi_{impl}. \quad (3\text{-}11)$$

The value of the implementation factor ϕ_{impl} will depend on several parameters, most importantly on

- Target BER/BLER;
- Wireless channel properties.
- Modulation and coding scheme.
- Choice of waveform.
- Level of RF impairments and their impact on the waveform.
- Receiver algorithms (channel estimation and equalization, symbol demapping and decoding).

From (3-10) and (3-11), it can be seen that the parameters through which the choice of waveform influences coverage is OBO and ϕ_{impl}. The value of OBO is directly connected with power efficiency of a waveform – with small envelope variations, OBO will likewise be small and waveform power efficiency high. On the other hand, ϕ_{impl} is impacted by the choice of waveform as well as waveform's robustness to RF impairments and to time-frequency selectivity of the channel. Another factor often related to ϕ_{impl} is the complexity of the implementation of waveform-related signal processing. More specifically, if a waveform can be processed in several different ways, often a more complex processing algorithm (e.g. involving trellis-based sequence detection or iterative equalization and decoding) will yield smaller ϕ_{impl} (and hence improve coverage) at the cost of increased complexity.

3.4.2.2.2 Energy Efficiency

Energy Efficiency (EE), in a form often used in the analysis of communication systems, is defined as the ratio between the bitrate and power expended by the communication system. This form, joining together two elementary system design parameters, is often chosen because of its tractability. Bitrate and expended power can incorporate different things, depending on the scenario being analysed.

There are two main types of EE: system EE and node EE. System EE considers the sum of bitrates in a system with several nodes (e.g. a base station and several users in a cell) and the sum of power consumptions of all the nodes. Impact of the choice of waveform on the system EE can be considered limited. Namely, the choice of waveform influences on the most part the implementation complexity of transceivers and PA efficiency, which may have some implications on total system power consumption; however, system topology (e.g. use of picocells/femtocells and distributed infrastructure nodes) and MAC layer approaches (turning the nodes on or off depending on the traffic, e.g. by use of wake-up signals) often have a more significant impact on system EE.

On the other hand, individual node EE (ratio of bitrate supported by the node when transmitting or receiving and the power consumed by the node) can in some cases be significantly impacted by the choice of waveform. This is particularly applicable to power-constrained user equipment nodes, where a convenient choice of waveform may yield significant savings in transmitter and/or receiver complexity and subsequently power consumption. For instance, choosing a waveform with low envelope variations can result in a lower peak output power (if coverage is to be maintained), which may in turn lower the power consumed by the PA and improve the EE. As another example, use of a waveform based on 1-bit quantization and oversampling [NDH+20] can result in use of more power-efficient analogue and mixed-signal circuitry in the transmitter and receiver which may also result in a reduction of power consumption and consequently higher EE.

3.4.3 Summary of Waveform Candidates

As presented in the section on waveform KPIs, certain waveform characteristics will be of higher importance than others when considering operation at frequencies beyond 100 GHz. Namely, power efficiency and robustness to HW impairments are given higher priority than spectral efficiency and frequency allocation flexibility, which represents a certain contrast with the waveform design requirements that were given priority in previous generations of wireless networks.

OFDM can continue to present a viable alternative in some scenarios, especially at lower frequencies and in situations where good interoperability with MIMO and flexible frequency allocation to multiple users is required. However, there is a general interest in finding waveforms that are more suitable for the novel constellation of design requirements. This section gives a short overview of a set of waveforms that may be considered of interest alongside OFDM, given in the frame of reference based on relevant waveform KPIs. It should be noted that this is not a comprehensive survey of existing waveforms but an overview of waveforms that are identified to be of interest for investigation in WP2.

3.4.3.1 Zero-Crossing Modulation (ZXM) with Temporally Oversampled 1-bit Quantization

The basic idea of this waveform is application of temporal oversampling and 1-bit quantization at both transmitter and receiver. At the transmitter, a combination of Faster Than Nyquist (FTN) signalling with the use of Run Length Limited (RLL) sequences enables the encoding of the information in the zero-crossings of the signal on a fine-grained temporal grid. At the receiver, the signal is quantized with a 1-bit ADC, concatenation of FTN and channel is equalized using a soft-output equalizer based on the BCJR algorithm and the RLL sequence is decoded using a second BCJR algorithm.

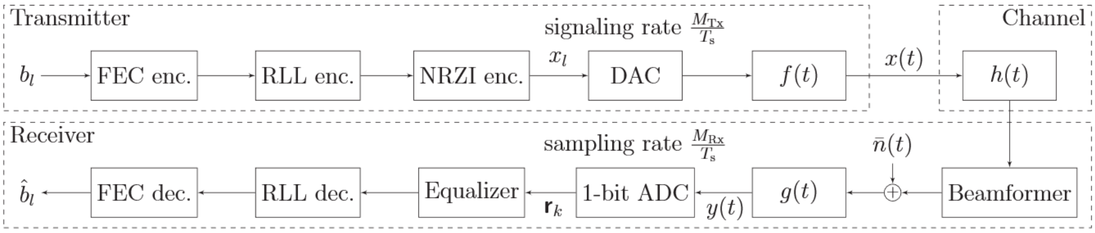


Figure 3-21: Complex-baseband equivalent of transmitter and receiver chains for ZXM with 1-bit quantization and oversampling (taken, with permission, from [NDH+20]).

This approach results in spectral efficiencies of 2 – 4 bps/Hz with the modulated signal having only 2 amplitude levels. An extension of the ZXM consists in transmitting a temporal derivative of the ZXM waveform, which results in improved energy efficiency in case of low data rates and provides a promising waveform alternative for joint communication and sensing. An advantage of ZXM with oversampled 1-bit quantization is relaxation of hardware requirements in the transmitter and receiver, primarily in the ADC and DAC. More relevant information can be found in [FDB+19], [NDH+20], [RDF21].

3.4.3.2 Analogue Multicarrier

At the transmitter, a wideband digital baseband signal is divided up into K narrowband signals, each transmitted using a separate, narrowband transmit chain on carrier frequencies ensuring (quasi) orthogonality between different subcarriers. The signals are added for a single-stream transmission using an analogue antenna array. At the receiver side, the analogue subcarriers are received using separate narrowband receiver chains. The method aims at relaxing the hardware requirements of the transmitter and receiver, primarily the ADC but with possible implications also on the PAs (reduced OBO) and other blocks due to narrowband operation in individual Tx/Rx chains.

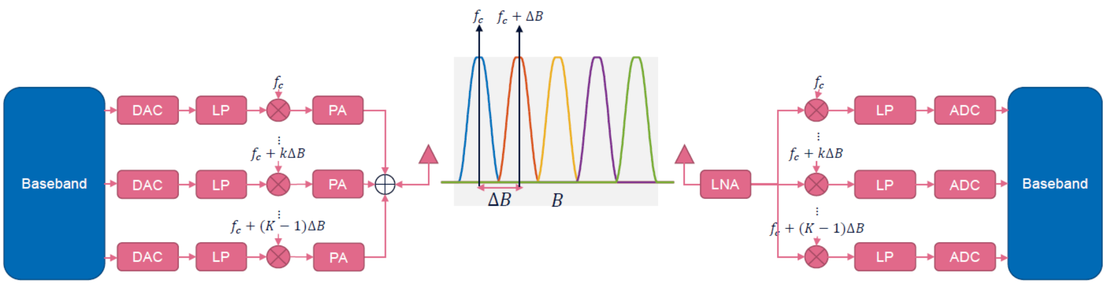


Figure 3-22: Concept sketch of the transmitter and receiver for analogue multicarrier.

3.4.3.3 DFTS-OFDM

Known also as DFT-precoded OFDM or Single-Carrier Frequency Division Multiple Access (SC-FDMA) in a multiuser context [MLG06], this scheme is a variation on OFDM where a DFT block (precoder) of size M is inserted in the OFDM transmitter prior to mapping the QAM symbols on OFDM subcarriers. Importantly, $M < N_{IDFT}$, where N_{IDFT} is the length of the DFT in the OFDM transmitter. DFT-precoding reduces the PAPR of the resulting time-domain signal compared with ordinary OFDM and thus results in lower PA OBO, which is the primary strength of this waveform and the reason why it was adopted in the uplink of LTE and NR.

Since coverage and power efficiency are identified as highly important design waveform design criteria for B5G/6G, DFTS-OFDM continues being highly relevant. Some detailed aspects of DFTS-OFDM and related signal processing are of particular interest in the B5G/6G and deserve a more thorough investigation. They include use of nonlinear receiver structures (such as DFE and turbo equalization) [BDF+10], [BZM+18] for improved error-rate performance – smaller

ϕ_{impl} in (3-10) and further improved coverage; implementation-friendly and flexible transceiver structures for DFTS-OFDM; further investigations into robustness of DFTS-OFDM to RF impairments generated by ultra-high-frequency RF hardware; exploration of trade-offs between power efficiency and Rx sensitivity.

3.4.3.4 SC-FDE

An alternative waveform to DFTS-OFDM, sharing with DFTS-OFDM the properties that make it attractive for application in B5G/6G (reasonably high power efficiency and good robustness to HW impairments), is the true single carrier with frequency-domain equalization. Indeed, some works analyse the two waveforms under the same analytical framework [BDF+10]. Some aspects of SC-FDE, particular for application in B5G/6G, deserve further investigation. These are, in particular, techniques of PAPR reduction; efficient DSP processing; in-depth analysis of techniques enabling frequency-domain equalization (cyclic prefix/guard interval/unique word) as well as alternative DSP approaches with equivalent effect (e.g. overlap-add); and investigating the importance of the choice of pulse shape in the trade-off between PAPR reduction, complexity and support for multiband operation.

3.4.3.5 CPM-DFTS-OFDM and ceCPM

Single-Carrier Frequency Division Multiple Access (SC-FDMA) employing a sub-sampled Constant Phase Modulation (CPM) encoder as precoder of SC-FDMA with I-FDMA (interleaved FDMA) subcarrier mapping, has been suggested as an energy-efficient constrained-envelope coded-modulation multiple-access scheme with potential applicability for, in particular, the M2M [WPS11]. The reason is that CPM-SC-FDMA yields very good envelope properties, down to a fraction of a dB, while at the same time maintaining the OFDMA structure. This allows for a simple multiple access scheme through frequency division and permits coexistence with adaptive OFDMA and reuse of the OFDMA transceiver structure currently in use in OFDMA-based systems. The scheme might also be useful for high bandwidth and coverage limited mmW scenarios with high requirements on transceiver energy efficiency and robustness to non-linear PAs, e.g. due to cost and severe peak power limitations, but with modest requirements on spectral efficiency due to large available bandwidth and dense reuse enabled by short transmission distances.

An alternative approach is the constrained envelope CPM (ceCPM) scheme, which is a true single carrier coded modulation scheme that generalizes CPM by allowing a controlled small amount of envelope variations. The framework allows signal design such that the receiver sensitivity can benefit proportionally from the allowed envelope variations energy. ceCPM is based on the extended Laurent decomposition [Lau86], [MM95], allowing non-binary modulation alphabets for spectrally efficient schemes. A detailed definition of ceCPM is available in [SS03], and key design aspects of ceCPM has been presented in [SS09]. Further details and investigations of ceCPM are available in [Sve02].

Both CPM-SC-FDMA and ceCPM can be detected by a low-complexity close-to-optimal Viterbi detector using Reduced State Sequence Detection (RSSD) with 8-16 states [Sve02]. CPM-SC-FDMA supports frequency diversity towards fading and narrowband interference, but at the cost of lower spectral efficiency compared to ceCPM that is best suited for less frequency selective channels to avoid complex Viterbi equalizer. Both schemes can benefit from an optimization of minimum Euclidean distance under a spectrum constraint function, the higher allowed side-lobes the better receiver sensitivity [Sve02].

3.4.4 Comparison of Waveform Candidates and Legacy Waveforms with Respect to Waveform KPIs and Identification of Open Research Problems

In addition to presenting the main features of waveforms deemed suitable for supporting the operation in B5G/6G systems, it is instructive to also give a concise rating of each of the presented waveforms with respect to the KPIs from Chapter 2. These ratings are collected in Table 3-7.

Table 3-7: Ratings of selected waveforms with respect to KPIs from Section 3.3.3. H = high, M = medium, L = low, M/L = medium to low, M/H = medium to high, O = open problem.

KPI / Waveform	PE	SE	Robustness to HW impairments	Complexity	Latency	MIMO compatibility	Frequency resource allocation flexibility (multiuser)	Robustness to TS channels	Robustness to FS channels	OOB reduction capability	Multiband capability (single user)	BW scaling
OFDM	M/L	H	M/H	M/L	M/L	H	L	M	H	M	H	H
ZXM	M	M/L	O	L	L	H	L	O	O	H	H	M
Analogue MC	H	H	O	H	L	H	H	H	H	M	H	M
DFTS-OFDM	M	H	M/H	M	M/L	M	H	M	H	M	H	H
SC-FDE	M	H	M/H	M	M/L	M	M/L	M	H	H	H	H
CPM-DFTS-OFDM	H	L	O	M/H	M/L	O	H	O	O	H	H	H
ceCPM	H	M	O	M/H	L	O	M	O	O	H	H	H

When rating a waveform with respect to a particular KPI, special attention was given to possible trade-offs with other KPIs. In cases where such trade-offs are pronounced, the "cost" of achieving a rating for a certain KPI considering other KPIs was considered. To name one example, for DFTS-OFDM, robustness to phase noise can directly be traded with the robustness to frequency selective channels through the choice of numerology (subcarrier spacing). Robustness to FS channels was rated as high, which increases the cost of robustness to phase noise and decreases the overall rating for robustness to HW impairments. Another typical trade-off is between the robustness to HW impairments and complexity. In general, a "good" rating (e.g. high power efficiency for ceCPM) is assigned if it comes at a reasonably low cost with regards to other KPIs.

When it comes to the main topic of the discussion – gap analysis, several important points can be discerned:

- All waveforms except OFDM score reasonably well in power efficiency, which is a highly important KPI. Possible room for improvement in ZXM, DFTS-OFDM and SC-FDE should be investigated.
- Robustness to HW impairments, another highly important KPI, is largely uninvestigated and should form a major part of the investigations in the scope of this project. Even for the relatively well studied DFTS-OFDM and SC-FDE, it is of interest to analyse the robustness to RF impairments at upper mmW frequencies using the impairment models for hardware operating in that specific frequency range.
- There is an overall need for investigating whether the implementation complexity – third KPI of high importance – can be reduced.

- Trade-offs between the three highly important KPIs (power efficiency, robustness to HW impairments, implementation complexity) should be thoroughly investigated.
- All candidate waveforms score remarkably well for the KPIs determined to be of medium to high importance (OOB reduction capability, multiband operation capability and bandwidth scalability).
- Robustness to time- and frequency-selective channels needs further investigation for some of the more novel waveform candidates.

These observations should be used as basic guidelines in the investigations on waveforms suitable for operation in B5G/6G.

3.5 Beamforming Related Gaps

3.5.1 Analysis Methodology

Considering the targeted KPIs and other system parameters including, channel, bandwidth, power amplifier and ADC constraints, first, the antenna and beam parameters will be determined, as sketched in Figure 3-23. Thereafter, the antenna types, beamforming architecture, and beam management strategies will be determined with the consideration of minimizing the complexity and improving energy efficiency. Accordingly, to determine gaps of the technology, the recommended design requirements will be compared to the available technology. This section provides a high-level overview, whereas Section 3.2 discusses the requirements and Section 3.3 is dedicated for analysis of individual hardware components.

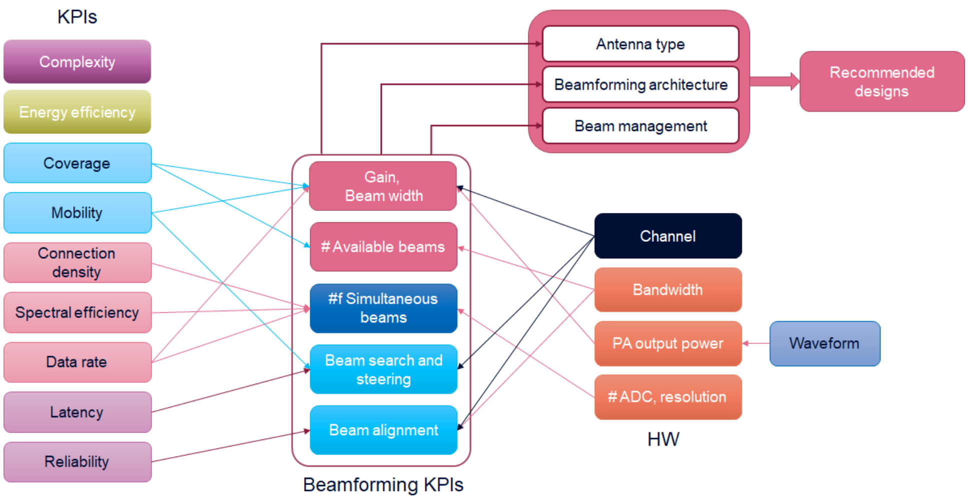


Figure 3-23: Beamforming KPIs in relation to system and link KPIs and HW.

3.5.2 Gain and Beam Width

To achieve the targeted data rate per link in the THz band, it is essential to increase the transmit and receive antenna gain. This is required to improve the link budget shown in Figure 3-24 by compensating for the reduced antenna aperture and the increased noise associated with very large bandwidth, as discussed in Section 3.3. However, the beam width becomes narrower as the gain gets higher, and this limits the coverage area of a single beam. Achieving high gain requires increasing the antenna aperture. This can be done by means of different antenna types including reflectors, lenses, or antenna arrays, as discussed in Section 3.3.6. The feasibility and necessity of integration of an antenna type can be determined from the communication scenario and involved devices. Note that a narrow transmit beamwidth can reduce the ability of a potential attackers to eavesdrop the communication. In the receiver the beam can be designed to increase robustness regarding jamming.

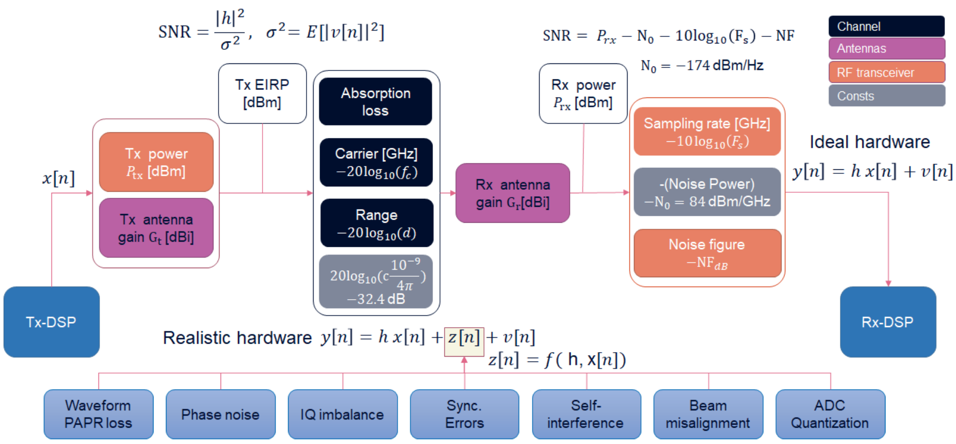


Figure 3-24: Link budget and the role of antenna gain.

3.5.3 Number of Available Beams

Reflectors and lenses provide a single fixed beam, which make them suitable for fixed links. The reflector might be used for backhaul applications, whereas, lenses for fixed user devices. To increase the coverage, multiple beams are necessary to cover a wider angle. For that, antenna arrays employing phase or delay shifts allow flexible switching between different beams, as presented in Section 3.3.6. However, to achieve high gain many antenna elements and power amplifiers are required. The number of antennas can be determined from the required beam directivity and array gain to compensate for PA output power limitations. In addition, the antenna coupling effect needs to be also considered, which depends on the array structure and distance between elements. Moreover, the ADC needs to have sufficient resolution at a very high sampling rate, as shown in Section 3.3.4.

3.5.4 Number of Simultaneous Beams

Depending on the targeted connection density and the required data rate per user, several users should be served at the same time in different angles. To achieve that, multiple beams should be available for providing multiple links. This can be achieved by employing multiple fixed beams using lenses or resorting to the antenna array solution with analogue beamforming. In both cases more ADCs are to be integrated, and this provide flexibility in employing hybrid analogue and digital beamforming by means of additional digital precoding.

3.5.5 Beam Search, Steering and Alignment

To support mobility, Section 3.2.2, and low latency, the switching from one beam to another needs to be fast enough when analogue beamforming is used. However, because of the limited number of beams, i.e. limited angular resolution, a successful beam alignment may not be guaranteed, which affects the link reliability. On the other hand, fully digital beamforming can digitally perform fine steering at the cost of increased complexity in terms of signal processing and implementation as the number of RF chains should be the same as the number of antennas. Nevertheless, the digital approach requires much less ADC resolution. Hybrid beamforming arises as a reasonable trade-off and it allows increasing the angular resolution [SY16]. Beam steering and alignment performance depends on the bandwidth ratio, where a value larger than 10 % brings new challenges.

3.5.6 Design Options and Challenges

Table 3-8: Design options and challenges related to beamforming.

	Options	challenges
Antenna types	Reflector, lens, array	Size, number, integration
Beamforming architecture	Analogue, digital, hybrid, multiple fixed beams	ADCs, processing complexity, integration
Beam management	Codebook selection, adaptive, localization-assisted	Narrow beams, mobility, latency, processing complexity

The implementation of the candidate options will be studied in relation to the hardware requirements for implementation, as discussed in Section 3.2 and Section 3.3 related to the implementation options summarized in Table 3-8.

3.6 Distributed MIMO Related Gaps

3.6.1 Background and motivation

Massive MIMO and Joint Transmission Coordinated Multi-Point (JT-CoMP) are two of the physical-layer wireless technologies that have attracted the most attention during the past ten years. In massive MIMO networks, each Base Station (BS) is equipped with a large number of antenna elements and serves numerous User Equipments (UEs) simultaneously by means of highly directional beamforming techniques [Mar10], [ABC+14], [JMZ+14], [BHS18]. On the other hand, JT-CoMP enables coherent transmission from clusters of BSs to overcome the inter-cell interference within each cluster [GHH+10], [JMZ+14], as illustrated in Figure 3-25.

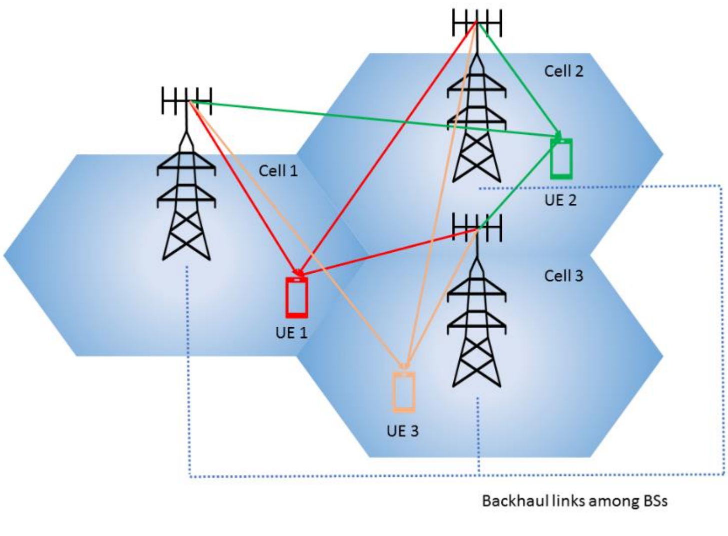


Figure 3-25: Illustration of JT-CoMP.

CoMP transmission and reception are particularly suited for increasing the system throughput of cell-edge users having a relatively long distance from the serving BS and adverse channel conditions (e.g., higher path-loss and interference from neighbouring BSs). Such scenarios have been widely studied over the past decade under the context of 4th generation (4G) systems [TPK09], [TCJ08], [IDM+11], [NMH14]. For example, it is shown in [NMH14] that JT-CoMP increases the coverage by, up to, 17 % for general users and 24 % for cell-edge users compared to non-cooperative scenarios. The beyond 4G EU FP7 ARTIST4G project reported an achievable spectral efficiency gain for JT-CoMP of up to 140 % compared to multi-user MIMO by a combination of interference floor shaping, user-centric clustering, user grouping, and a two stage scheduler [ARTIST4G-D1.4], but at the expense of a significant uplink feedback overhead and downlink reference signal overhead. Techniques, such as, JT, Coordinated Beamforming (CB) and Dynamic Point Selection (DPS) were standardized in 3GPP and are supported by the Long Term Evolution-Advanced (LTE-A) [IDM+11].

While the 5G NR standard has massive MIMO as one of its cornerstones, it does not include JT-CoMP (at least in its first releases) as its Long-Term Evolution (LTE) standardization [LSC+12] did not found significant gains in practical deployments. This can be mainly attributed to the considerable amount of backhaul signalling for Channel State Information (CSI) and data sharing resulting from a network-centric approach to coherent transmission [IBN+19], whereby the BSs in a cluster cooperate to serve the UEs in their joint coverage region. The practical implementation of JT-CoMP was also hindered by other attributes of LTE, such as frequency division duplex operations and a rigid frame/slot structure, which did not allow for effective channel estimation.

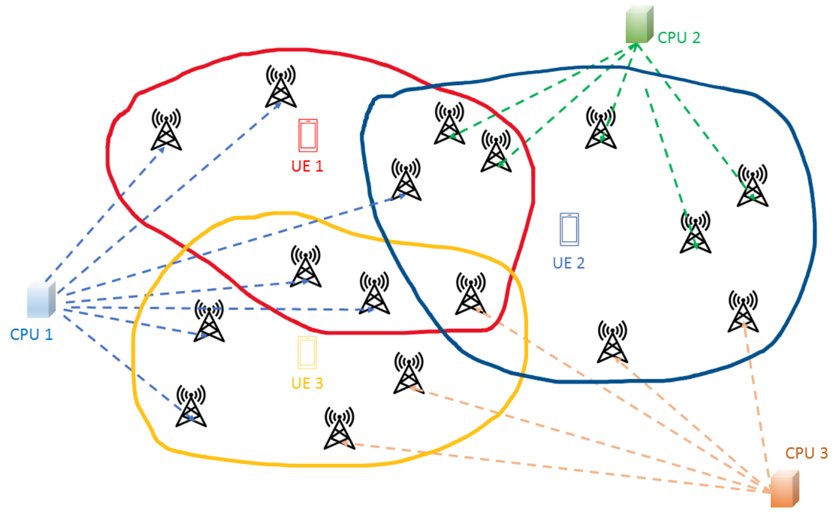


Figure 3-26: Illustration of cell-free massive MIMO.

Cell-free massive MIMO [IBN+19], [ZCL+19] is a recently coined concept that conveniently combines elements from small cells [JMZ+14], massive MIMO [BHS18], and UE-centric JT-CoMP, cf. "Cover-Shifts" in [JMZ+14] and more recent works in [BDZ+19], as illustrated in Figure 3-26. The basic idea of a cell-free system was however proposed and analysed already in [XWT+13], but there it was denoted as resource pooling for a frameless network architecture. In UE-centric coherent transmission, the clusters of BSs are formed such that each UE is served by a few of its closest BSs, i.e., each BS cooperates with a per-UE defined sub-set of BSs. In a cell-free context, the massive MIMO regime is achieved by spreading a large number of antenna elements across the network (even in the form of single-antenna BSs [NAY+17], [NAM+17]), which provides enhanced coverage and reduced pathloss. Moreover, a UE-centric coherent transmission extended to the whole network, where each UE is served jointly by all the BSs, allows to entirely eliminate the inter-cell interference, as shown already in the pioneering Network MIMO paper [FKV06]. To this end, all the BSs are assumed to be connected to a Central Processing Unit (CPU) by means of backhaul links, which together provide the UE-specific data and, possibly, enable network-wide processing for the computation of the BS-specific precoding strategies.

3.6.2 State of the art

3.6.2.1 Cooperative MIMO systems

Cooperative precoding design for JT-CoMP can be broadly classified into centralized and distributed approaches. In the centralized precoding design, the BS-specific precoding strategies are computed by the CPU based on the CSI locally acquired at each BS and are subsequently fed back to the corresponding BSs via backhaul signalling. Here, the computational complexity involved in the precoding optimization at the CPU may be overwhelming due to the high dimensionality of the involved channels. In the distributed precoding design, the BS-specific precoding strategies are computed by the BSs (with a significant complexity reduction) in an iterative best-response fashion based on local CSI and additional information from the other BSs, which is traditionally obtained via backhaul signalling [TPK11], [KTJ+18]. In both cases, the amount of CSI exchange via backhaul signalling (either between the BSs and the CPU or among the BSs) represents a major obstacle to the practical implementation of JT-CoMP when the number of BSs and UEs grows large; in addition, the backhaul introduces delays in the CSI exchange that can significantly degrade the performance of the precoding design. Some works have been performed on feedback and backhaul constrained JT-CoMP, cf. e.g. [LTS16, LTD+16] and references therein, as well as on reducing delays by semi- and fully distributed JT-CoMP, cf. e.g. [HLS13] and references therein, taking also unreliable backhauling into account.

Large distributed and cooperative MIMO systems (D-MIMO), aka cell-free massive MIMO, has been the subject of an extensive literature over the past few years and is now regarded as a potential physical-layer paradigm shift for beyond-5G systems [ZBM+20]. Remarkably, cell-free massive MIMO networks have been shown to outperform traditional small-cell and cellular massive MIMO networks in several practical scenarios [NAM+17], [NAY+17], [BS20]. Their performance has been analysed under several realistic network and hardware assumptions, e.g., with hybrid analogue-digital precoding [ABZ+19], with low resolution ADCs [HZC+19], [ZZQ+19], under channel non-reciprocity [PRG+19], and with hardware impairments and limited backhaul capacity [ZWB+18], [ME19], [FR19]. Another important focus is on the global energy efficiency, which has been tackled considering the impact of backhaul power consumption [NTD+18] and quantization [BCB+19] among other factors. To avoid the CSI exchange among the BSs via backhaul signalling as well as the overall computational complexity, most of the aforementioned works assume simple non-cooperative precoding strategies at the BSs, such as Matched Filtering (MF), local Zero-Forcing (ZF), and local Minimum Mean Square Error (MMSE), which can be implemented based on local CSI (see also [IKB+19]). However, the performance of cell-free massive MIMO systems can be considerably improved by increasing the level of cooperation among the BSs [BS20].

The scalability issues of D-MIMO are particularly noticeable in a cell-free massive MIMO context due to the large number of involved BSs and UEs. The performance gains brought by cooperative precoding design over its non-cooperative counterpart become even more important in cell-free massive MIMO as the channel hardening effect is less pronounced than in cellular massive MIMO [IBN+19]. However, non-cooperative precoding strategies (such as MF, local ZF, and local MMSE) have so far been preferred in the cell-free massive MIMO literature as they do not require any CSI exchange via backhaul signalling, thus mitigating the scalability problem. Some recent works can be found in [AGT21].

3.6.2.2 Cooperative MIMO at mmW Frequencies

mmW communication not only provides relatively large system bandwidth but also the possibility of packing a significant number of antenna elements for highly directional communication [RSM+13], which is important to ensure link availability as well as to control interference in dense deployments [ABC+14]. Thus, mmW mobile communication is anticipated to substantially increase the average system throughput.

There are still many issues that need to be resolved before these technologies can fulfil reasonable availability requirements. The fundamental challenge is the sensitivity of the mmW radio channel to blockages due to reduced diffraction, higher path, and penetration losses [MRR17]. These lead to rapid degradation of signal strength and give rise to unstable and unreliable connectivity. Furthermore, connection reliability is aggravated by the fact that, for instance, a human blocker can degrade the channel quality by 30 dB for up to hundreds of milliseconds [MRR17]. Presence of such frequent and long duration blockages significantly reduce the quality-of-service. To overcome such challenges, use of D-MIMO (CoMP, cell free massive MIMO) schemes, where the users are concurrently connected to multiple BSs, are imperative for more robust communication [TPK09], [TCJ08], [IDM+11], [NMH14], [MRG17], [MR19], [MDT16], [SPK17], [LC17]. It is envisioned that joint transmission and reception via spatially separated transceivers will be vital in upcoming 5G systems [37.340].

Recent studies have considered the deployment of CoMP in the mmW frequencies [MRG17], [MR19], [MDT16], [SPK17], [LC17], [FML+21]. Also, it is proposed in 3GPP specifications as a key component for upcoming 5G systems [37.340]. In [MRG17], [MR19], the authors showed significant coverage improvement by simultaneously serving a user with spatially distributed transmitters. Results were drawn from extensive real-time measurements for 73 GHz in the urban open square scenario in Brooklyn. The network coverage gain for the heterogeneous mmW system was also confirmed in [MDT16] using stochastic geometry tools. The work in [SPK17], proposed a low complexity cooperation technique for the JT, wherein a subset of cooperating BSs is obtained by selecting the strongest BS in each tier. The authors also provided the impact of blockage density in multi-tier heterogeneous network. Similar to earlier works on two-stage hybrid analogue-digital beamforming design e.g., in [ALH15], [YSZ+16], authors in [LC17] extended for JT-CoMP in multi user massive MIMO systems with a high-dimensional analogue RF precoder followed by a low-dimensional centralized digital baseband precoder. In [FML+18] cooperative mmW networks with hybrid precoding architectures were investigated. The precoders were optimized for energy efficiency under per-user rate targets, and the cooperation was performed using spatial multi-flow to minimize the user data sharing overhead. More recent work can be found in [KKT21].

It is well known that a system can provide any level of reliability by sequential data transmission, i.e., by retransmitting the same message at various protocol levels, until a receiver acknowledges correct reception over a dedicated feedback channel [JWE+15]. However, in the presence of random link blockage and high path-losses, mmW feedback links are equally unreliable and thus results in redundant retransmission. On the other hand, allowable latency determines a strict upper limit on the number of retransmission attempts [SLU+16]. The loss of connection in the mmW communication is mainly due to a sudden blockage of the dominant links caused by abrupt mobility, self-blockage, or external blockers [MRR17]. Accurate estimation of each blocker requires precise environment mapping and frequent CSI acquisition, which might result in significant coordination overhead and severe synchronization challenges. Furthermore, blockage events can create large latencies if a passive hand-off is inevitable [SLU+16]. A recent work can be found in [KJT20].

3.6.2.3 Wireless Backhaul/Fronthaul

Efficient wireless backhaul fronthaul is a crucial enabler for successful deployment of distributed large MIMO systems. As summarized in [RAB+20], at mmW frequencies and above, there is a need for dense network deployments to mitigate the reduced coverage at these bands due to constraints in the propagation environment and hardware limitations in the transceivers. Such dense deployments make backhauling/ fronthauling challenging in these bands. In particular, it is expensive and cumbersome to roll out fibre links to all the APs. However, the presence of very wide bandwidths at these carrier frequencies makes it possible to include the wireless backhaul/fronthaul in the same spectrum as the wireless access. For this reason, Integrated Access and Backhaul (IAB) network configurations seem promising, where a few (potentially, fibre-

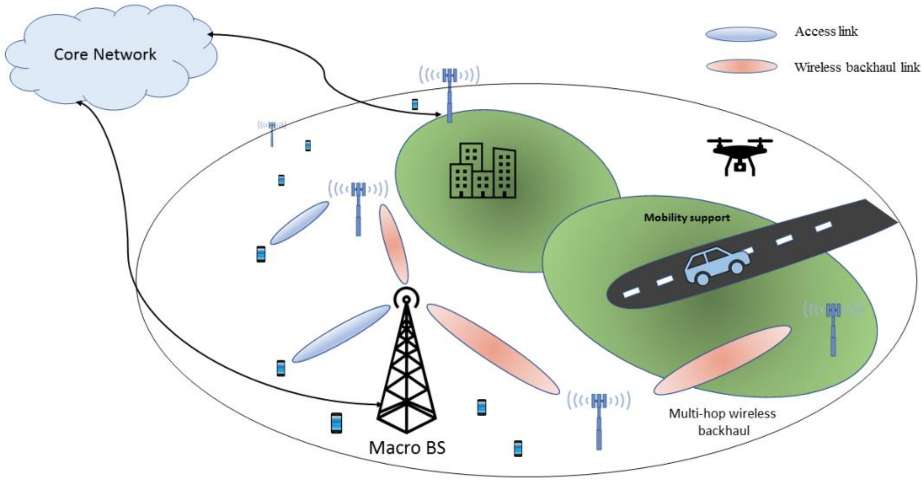


Figure 3-27: Illustration of IAB.

connected) APs provide other APs as well as the mobile devices inside their cell area with wireless backhaul and access connections, respectively, as illustrated in Figure 3-27.

IAB networks are different from conventional relay networks because the information load changes in different hops. Particularly, as the number of mobile devices per hop increases, the APs need to transfer the aggregated data of multiple mobile devices accumulated from the previous hops. In addition, the interference on the links will depend on the information load. Some early work has been performed, see e.g. [MMF+20, RAB+20] and references therein. Given the fact that 6G networks will see an even greater level of densification and spectrum heterogeneity than 5G networks, it is expected that IAB networks will play a major role, especially in mmW and (sub-)THz carrier frequencies.

3.6.3 Distributed MIMO Gap Analysis

Research on distributed large MIMO systems for Beyond 5G/6G are still needed to be conducted in several areas, such as

- Scalability for availability, such as distributed joint precoder/decoder design without CSI exchange
- Precoding schemes (especially for the upper mmW bands) including joint multi-tx/multi-rx with HW and backhaul-fronthaul constraints awareness
- Precoding (and other resource allocation) schemes in case of multi-antenna UEs
- UE beamforming
- 3D cell-free massive MIMO systems employing vertical coordination/cooperation
- Wireless mesh networking in converged backhaul/fronthaul and access for reliability
- IAB in cell-free massive MIMO, including full duplex
- Converged IAB for cell-free massive MIMO, in which nodes can act as both access and backhaul nodes
- Cell-free massive MIMO using (sub-)THz bands for backhaul/fronthauling, access and joint access/backhaul/fronthauling
- Heterogeneous spectrum use in cell-free massive MIMO systems, in which lower bands are used to assist and coordinate access/backhaul/fronthauling at higher bands
- Distributed large MIMO systems using Reconfigurable Intelligent Surfaces (RIS)
- Interference handling in integrated access backhaul and pure fronthaul in mesh configurations operating beyond 100 GHz using beamforming/MIMO

- Dynamic blocking mitigation in mmW bands, enabled e.g. by location and mapping information
- Mobility support in cell-free massive MIMO systems

Furthermore, architecture and functional split options need further attention, in particular:

- Centralized L1 processing (low HW complexity of distributed APs) versus Distributed L1 processing (more complex HW in distributed APs but reduced requirements on fronthaul)
- Fronthaul tradeoffs, e.g. wireless serialized vs. parallel, optical vs. electrical, time-domain (e.g. C1 interface) vs. frequency domain (e.g. C2 interface), radio-over-fibre, etc
- Optimizing traffic routing to minimize interference on layer 1 due to centralized or distributed resource sharing
- Joint user centric dynamic AP clustering and load balancing, including blocking mitigation and energy efficiency optimization also needs further research.
- Multi-CPU coordination of access points.

In addition, system performance evaluations of distributed large (cell-free) MIMO are lacking, considering

- Realistic deployment options
- Hardware impairments
- Traffic models
- Scalability limitations
- Synchronization limitations
- Non-coherent operations in higher bands

3.6.4 Hexa-X planned activities

To this end, in Hexa-X Task 2.5 will investigate enabling techniques for scalable distributed large antenna systems with converged access-backhaul-fronthaul in beyond 5G/6G systems towards seemingly infinite network capacity. Initial focus will be on mmW bands for access and various fronthaul/backhaul solutions, including above 100 GHz wireless mesh networks based on state-of-the-art transceivers, targeting key open research questions. In the second phase, the studies will embrace the constraints at THz bands for access, by building on the work in the other WP2 tasks.

Research will be conducted on system performance evaluations of distributed (cell-free) large MIMO, considering realistic deployment options, hardware impairments, traffic models, scalability limitations. Architecture and functional split options on the communication layers, ranging from fully centralized to fully distributed, will be studied e.g. centralized L1 processing (low HW complexity of distributed APs) versus distributed L1 processing (more complex HW in distributed APs but reduced requirements on fronthaul). Fronthaul tradeoffs will also be studied, e.g. wireless serialized vs. parallel, optical vs. electrical, time-domain (e.g. C1 interface) vs. frequency domain (e.g. C2 interface), radio-over-fibre, etc.

Integrated wireless access, backhaul and pure fronthaul in mesh configurations at mmWand above 100 GHz will be studied with a special focus on interference handling using beamforming/MIMO, and to optimize traffic routing to minimize interference on layer 1 due to centralized or distributed resource sharing. Distributed HW-aware precoding techniques will be developed including joint multi-tx/multi-rx with backhaul-fronthaul constraints awareness. User centric dynamic and scalable clustering and load balancing techniques will be developed, taking blocking mitigation and energy efficiency into account.

The expected outcome of the task are novel enabling techniques, architectures and system evaluations showing the potential of scalable distributed large antenna systems with converged access-backhaul-fronthaul at mmW and (sub-)THz bands for seemingly infinite network capacity in Beyond 5G/6G systems.

3.7 Channel Model Related Gaps for above-100 GHz Radios

This section reveals gaps of our present knowledge about above-100 GHz wave propagation measurements and modelling according to literature survey. Radio wave propagation, generally available in the form of channel models for radio link and system design and evaluation, affects the following KPIs mentioned in Figure 2-1; **bold** are KPIs and *italic* are features of a channel model.

- **Data rates** are related to receive the signal-to-noise ratio and hence *pathloss*.
- **Spectral efficiency** is related to the capability of spatial multiplexing and hence the extent of *multipath richness* and *polarization characteristics of wave propagation*.
- **Area traffic capacity** and **connection density** are related to the capability of spatial interference management and hence the extent of multi-user *spatial channel correlation*.
- **Energy efficiency** is related to the transmit power and channel estimation overhead and hence *pathloss* and *channel dynamics* when terminal changes its location and posture.
- **Latency** and **reliability** are related to retransmission of frames and hence *channel dynamics*.

The survey covers 1) wave-material interaction, 2) atmospheric losses and 3) multipath characteristics, as they are influential to the identified features of channel models. It must be noted that, the term channel model includes antenna characteristics at link ends, while the term propagation model does not [SMB+01]. This section covers the latter mainly.

3.7.1 Wave-material Interaction

Wave-material interaction affects all the identified influential channel features for the KPIs, i.e., *pathloss, multipath richness, multi-user spatial correlation, wave polarization* and *channel dynamics* because it governs the wave propagation directions and power (losses). The wave-material interaction specifically refers to reflection, diffraction, scattering and penetration. When analysing them, it is necessary to know material properties such as permittivity and conductivity, along with their shapes and dimensions. The most referenced source to know them would be the ITU-R P.2040 [ITU-R2040-1]. It specifies insulating and conducting parameters for various materials in our living space up to 100 GHz RF in the best case, but lacks those for above 100 GHz RF. The same applies to scattering and Radar Cross Section (RCS) models. Measurements that would complement this lack of parameters are summarized as follows.

3.7.1.1 Reflection and Scattering

Reflections from different materials found indoor and outdoor, e.g., plasterboard, plywood, concrete and wall papers among others are reported in [PJW+07, JPM+08, JPM+11, RXK+19, SZM+21, SKJ+21, OLJ+21] between 100 GHz and 1 THz with the effects of surface roughness. Due to the comparable wavelength at above-100 GHz with surface roughness, scattering is more pronounced than below-100 GHz RF. However, usually scattering is much weaker than specular reflections. Analyses of scattering from, e.g., a plaster, wall paper, brick wall and wood, show that the Kirchhoff theory and existing mathematical models of directive scattering, and Rayleigh-Rice scattering describe the measurements well [JPM+11, RXK+19, SZM+21]. Man-made metallic surfaces with controlled roughness are used to observe the scattered fields from 100 to 400 GHz RF, showing the effects of correlation length and heights of the roughness on the wave scattering pattern [MSZ+19].

3.7.1.2 Penetration and Blockage

Increased penetration losses for higher RF up to 10 THz are reported for commonly-found materials in our living spaces in [JPM+08, KLJ16, KLP+16, XR18, RXK+19, PEM+20, JWP+21]. Estimated refractive indices on the other hand show constant values between 100 GHz and 1 THz [PJM+07, JPM+08]. Blockage losses due to a human body are severer as the radio frequency increases up to 150 GHz according to the measurement reported in [IYK+21]. A geometrical model of human blockage loss estimation using a uniform theory of diffraction from knife-edges works well up to 150 GHz.

3.7.1.3 Radar Cross Section

RCSs are reported for a human body mannequin at 140 and 220 GHz, revealing the greater cross section as the frequency increases [AMZ+20]. Those for vehicles can be derived from measurements like [EPM+21] at 300 GHz, though the paper does not report an RCS estimate. RCSs of natural objects such as snow and a tree have been widely studied in the context of remote sensing, e.g., [HU90].

3.7.1.4 Identified Gaps on Wave-material Interaction

Despite the works, a missing piece of knowledge, still, is the relationship between below- and above-100 GHz; most papers mentioned in the following report results above 100 GHz only and do not consider continuity of the results with lower frequencies except for very latest paper [OLJ+21]. The measurement was performed on different materials and the material-dependence may be as significant as the frequency-dependence especially for the reflection coefficient. Measurement on the same material with the same measurement setup from centimetre wave up to THz frequency would be beneficial for the analysis of frequency-dependency in multipath properties.

3.7.2 Atmospheric Losses

3.7.2.1 Literature Survey

Atmospheric losses have been considered only for long-range backhaul links in the legacy context due to its marginal effects on losses. However, the losses may not be marginal for above-100 GHz cellular links as they may affect *pathloss, wave polarization characteristics* and *channel dynamics.* Multipath richness and multi-user correlation would be less affected by atmospheric losses because all multipaths are almost equally attenuated given a link distance.

Main mechanisms of the atmospheric attenuation are the molecular absorption and the specific attenuation due to rain and fog. The interaction with water vapour strongly causes frequency dependent absorption of radio waves, which is observed as an absorption spectrum with certain spectral lines [GRH+16]. Beer-Lambert's law can be used for modelling the molecular absorption as described in [TER18-D32]. It is affected by the density and the absorption cross section of molecules, which depends in the water vapour case on the temperature, humidity, and operating frequency. Additional attenuation can be experienced in outdoor links in heavy rain conditions. ITU recommendation specifies the rain attenuation up to 1 THz frequency in [ITUP838-05]. Fog and cloud attenuation are specified in recommendation [ITUP840-17] only up to 200 GHz.

3.7.2.2 Identified Gaps on Atmospheric Losses

Lacking experimental evidence about interaction between radio waves and atmospheric particles, particularly fog and cloud attenuation, is identified for higher than 200 GHz. The impact of rain drop size and shape is also a topic for future studies.

3.7.3 Multipath Characteristics

Wave propagation characteristics for cellular links are usually described as a set of multipaths, each of which arises from interaction of waves and material objects. Observation of multipaths from measurements allows more holistic characterization of wave propagation than looking at each physical wave-material and wave-atmospheric interaction. A mathematical model describing the abstracted wave propagation between link ends is called a channel model. Studies of multipaths therefore cover all influential features of channels to KPI, i.e., *pathloss*, *multipath richness*, *multi-user spatial correlation*, *wave polarization characteristics* and *channel dynamics*.

Existing papers show many experimental evidence of multipath propagation for above-100 GHz [PJJ+11, KKZ+15, PRK16, CKZ17, NJK+18, VZF+18, PD19, CSA19, GPH+19, XKJ+19, CZ20, CSZ20, DMS+20, AHN+20a, JXK+20, NHJ+21, EPM+21, JXK+21]. However, collective knowledge of multipath channels still requires extensive measurements for developing a comprehensive channel model that covers varying scenarios of, e.g., small-cells and long-range back/front-haul networks. Understanding about relationships between observed multipaths in measurements and physical objects in the environments that contribute to multipaths seem also lacking. The use of measured evidences of multipath channels for calibrating site-specific channel simulation tools, e.g., ray-tracing and ray-launching, seems not popular yet despite its importance for localization and tracking. The following summarizes the available knowledge about multipaths propagation for above-100 GHz RF.

3.7.3.1 Application Scenarios

Most papers cover short range indoor links up to 50 m of distance, including laboratory and office [PJJ+11, KKZ+15, PRK16, CKZ17, VZF+18, PD19, DMS+20, JXK+20], large halls such as shopping mall and airport [NJK+18, NHJ+21], data centre [CSA19, EDR+19, CZ20, CSZ20], desktop [PJJ+11, KZ15] and train-to-infrastructure communications [GPH+19] scenarios. Only one paper [AHN+20b] reports outdoor urban channel sounding of link distance up to 100 m.

3.7.3.2 Pathloss

Pathloss models cover 140 GHz [KKZ+15, CKZ17, NJK+18, PD19, AHN+20a, AHN+20b, JXK+20, NHJ+21], 190 GHz [DMS+20] and 300 GHz [PJJ+11, KZ15, CKZ17, VZF+18, CSA19, GPH+19, EDR+19, CZ20, CSZ20] RF. As most measurements cover links with line-of-sight (LOS), their pathloss models are like the free-space formula where the pathloss exponent is close to 2. The pathloss exponent in NLOS indoor office scenario is 2.8 according to [JXK+20]. Pathloss models need to be independent of antenna gains at link ends ideally, which are called *omni-directional* pathloss model in many cases.

3.7.3.3 Delay and Angular Spreads

Multipath spreads over the propagation delay and angular domains represent frequency selectivity and spatial multipath richness of propagation channels. They are characterized by delay and angular spreads, respectively.

Measurements of indoor office omni-directional channels show Root Mean Square (RMS) delay spread up to 20 ns but mostly smaller than 10 ns [PD19, DMS+20, JXK+20], while it is reduced to 1 ns at 300 GHz according to a data centre environment [CSZ20]. In a large indoor hotspot, like an airport check-in hall, much greater delay spread up to 120 ns are reported [NHJ+21].

Papers [KKZ+15, CZ20] report the coherence bandwidth instead of the delay spread, which is roughly inversely proportional to each other. The coherence bandwidth is a more intuitively relevant metric than the delay spread to multi-carrier transmission such as orthogonal frequency division multiplexing. Both 110 – 170 GHz laboratory [KKZ+15] and 300 GHz data centre [CZ20] channels show the coherence bandwidth around 1 GHz.

Angular spread may be indicative for antenna correlation when link ends have arrays with multiple RF chains and hence allow spatial multiplexing similarly to legacy MIMO radios. Even for a single RF chain receiver, a set of analogue weights for maximum ratio combining, that maximizes the receive signal-to-noise ratio, becomes different as there are more multipaths than the line-of-sight. Indoor omni-directional channel measurements report mostly up to 50° and 10° azimuth and elevation spreads [JXK+20, NHJ+21, DMS+20], but sometimes up to 70° azimuth spread showing that multipaths arrive from many different directions. Outdoor 140 GHz measurements [AHN+20b] report up to 54° azimuth spread.

3.7.3.4 Small-scale Fading Models

In addition to delay and angular spreads, multipath cluster models are essential for proper characterization of small-scale fading of wave propagation channels. In the context of legacy cellular radios, the number of clusters can be roughly seen as the multipath richness. However, when antennas at link ends must form narrow pencil beams, multipath angular and power distributions *inside* clusters may also affect multipath richness. The following have been reported in terms of cluster characteristics at above-100 GHz.

- The number of clusters is up to 6 according to indoor office measurements [NJK+18, JXK+20].
- Intra-cluster azimuth spreads vary for measurements, probably because of differences in the resolution of sounders and clustering method. Intra-cluster azimuth spreads are up to 18° in indoor and outdoor channels [NJK+18, JXK+20, AHN+20b].
- Finally, small-scale fading of omni-directional 140 GHz indoor channels is reported in [SNL+21]. The paper shows that the fading in the LOS and obstructed-LOS conditions is well described by the Weibull and Nakagami-m distribution with the shape parameter m = 1 to 3, respectively.

3.7.3.5 Frequency Dependency

Finally, variation of the influential channel features, i.e., *pathloss*, *multipath richness*, *multi-user spatial correlation*, and *channel dynamics*, across radio frequencies would be our interest when extending the existing legacy channel models for above-100 GHz RF.

Radio wave propagation mechanisms due to waves' interaction with materials and objects, i.e., reflection, diffraction, scattering and penetration, show varying frequency dependency. For example, *reflection* coefficients of waves on a flat smooth surface do not much show frequency dependency and hence we can count on a power delivered through flat smooth metallic surfaces for example. *Diffraction* losses are known to become large as the radio frequency increases for the same incident and diffraction angles to a wedge (or building corner for example in practice). It is an open question how far a diffracted wave can be significant beyond a corner, compared to a reflected wave in, e.g., a street canyon. *Transmission* losses are also known to increase as the radio frequency because the wave attenuation constant in a dielectric medium is proportional to the frequency [ITU-R2040-1]. Finally, scattering on a surface seems to occur more often at above-100 GHz than the legacy band because a surface roughness can be more often comparable to the wavelength of ~2 mm at 150 GHz for example. However, whether the scattering on a rough surface can deliver meaningful power from one link end to another is still an open question because scattering in general does not have directivity as compared to reflection [JPM+11, RXK+19]. A combination of these propagation mechanisms constitutes multipath channels, which may show frequency dependency depending on the dominant propagation mechanism in the environment.

Comparisons of angular profiles of indoor multipath propagation at different RF, including below- and above-100 GHz [PRK16, VZF+18] report consistency of its spectrum shape across the tested RF because peaks corresponding to strong specular multipaths are found at similar angles.

Papers comparing 28 and 140 GHz bands show several insights. For example, Nguyen *et al.* [NJK+18] reports that the delay and angular spreads and cluster parameters at the two frequencies are similar in a large indoor hotspot, while Ju *et al.* [JXK+20, JXK+21] reports differences of delay spread and cluster angular spread between the two RF in an indoor office. A latest result by Olsson et al. [OLJ+21] revealed through their extensive indoor office measurements that the excess loss to the free-space pathloss is similar at 28 and 140 GHz RF. It is because the wave propagation is dominated by reflections in NLOS links and that reflection losses for the two RF are similar.

The channel model by 3GPP [38.901] includes several frequency-dependent models of large-scale parameters, e.g., pathloss, delay and azimuth angular spreads. They are defined up to 86 GHz, but a recent paper [NHJ+21] shows that the models fit measured large-scale parameters at 140 GHz well for indoor hotspots. A new set of channel model parameters, like the 3GPP one, was derived in [JXK+20, JXK+21] for an indoor office scenario at 28 and 140 GHz.

3.7.3.6 Identified Gaps on Multipath Characteristics

The literature survey on Terahertz cellular channel modelling shows the following gaps of insights to still complement through additional efforts.

- *Experimental evidence of multipath wave propagation*. Though reported measurements in the literature highlights pathloss and multipath characteristics such as angular and delay spreads well for indoor scenarios, those for outdoor scenarios may still under development due to lack of experimental evidence. Other scenarios like industrial, vehicular, and ground-to-air settings would also be of relevance. It is also important to note that a measurement campaign of a single site cannot reveal a full picture of multipath characteristics, necessitating **collective efforts of measurement campaigns** across scenarios, frequencies, link distances, mobility and geographical area (e.g., whether the site is located a temperate climate or with harsh winter).
- *Small-scale modelling of wave propagation*. Small-scale modelling includes fading distribution, Doppler, angular and delay spreads as well as spatial-temporal characteristics of clusters. The most detailed modelling of small-scale fading would be based on **clusters**, but their knowledge supported by experiments are extremely limited despite their relevance to an industry standard channel model. Similarly, **frequency dependency of small-scale fading models** has not been addressed, leading to non-existent mathematical model for them supported by experiments.
- *Understanding wave propagation mechanisms for site-specific cellular channel modelling*. The last identified gap is clear lack of analyses for **multipath wave propagation mechanisms** in relation to physical environments. It can be conjectured that Terahertz cellular radios can take advantage of physically very small scatterers to convey power from one communication device to the another, because physically small scatterers can become electrically large enough and hence can focus gains to favourable scattering/reflection directions. However, there is no evidence reported from experiments, yet that physically small objects can produce meaningful propagation paths. This insight is essential in making **site-specific cellular channel model** working, e.g., ray-tracing and launching, that take advantage of ray-optics approximation of radio wave propagation.

4 Next Steps

In this deliverable, a variety of new use cases for 6G has been described, and their requirements in terms of the various KPIs have been addressed. The practical realization of wireless systems for those use cases is not straightforward. A part of these use cases addressed in Chapter 2, e.g. long range fixed wireless access and backhaul, or shortrange hot spots could in principle be covered to a certain extent with an extension of existing solutions and standards. A larger part of intended use cases, e.g. short range access for mixed reality and telepresence, or industrial applications, or long range satellite to ground links, as well as the sensing and localization applications, represent completely new paradigms since here additional requirements like extreme bandwidth or short latency and increased reliability come into play. This implies the need for new system approaches. Some of the requirements of these systems are going far beyond what can be achieved with extension of currently known system approaches. Beneath data rate and coverage targets and delay and latency requirements also the need for high spectral efficiency and energy efficiency becomes obvious.

To find an efficient way to design future 6G upper mmW systems addressing the new requirements well, we first had to identify the different areas of limitations which cause challenges in system realization, and the resulting gaps towards the use case requirements, as described in Chapter 3. In the following sections a short summary of the identified main limitations related to the different tasks, and potential ways to circumvent them for the different target use cases are given.

In Task 2.2 the hardware limitations from the perspective of the devices for transmit and receive side is analysed. High frequency as well as high bandwidth lead to device parameters less favourable than at lower frequencies. These hardware limitations represent the most substantial impact on system design. They influence all other components of the system and overcoming these limitations will involve not only device and technology improvement, but also system design and HW architecture.

Therefore, Task 2.3 takes these limitations into account when searching for appropriate waveform design maximizing spectral efficiency and energy efficiency by addressing PA nonlinearity issues with low PAPR properties. At the same time, the waveform should be insensitive to the hardware introduced impairments like phase noise or low resolution analogue to digital converters. Several potentially suitable waveform candidates will be investigated with respect to the hardware introduced challenges.

The feasibility and advantages of the various beamforming architectures, addressed in Task 2.4, also strongly depends on the properties of the available hardware at upper mmW bands. High gain beamforming to overcome increased path loss, and spatial multiplexing capabilities to increase cell data rate are challenged by the need for high precision beam forming and the related new beam pairing schemes.

Task 2.5 focuses on scalable distributed large MIMO systems with focus on optimum system operation and also architectural and functional split options. Initially enhancements and extensions of MIMO schemes for more spectral efficiency in lower mmW frequency bands are addressed. Then in a second step, the application and potential under the upper mmW band physical layer and hardware constraints, identified in the other tasks, will be assessed as well.

Further, unknown properties of the channels at the targeted upper mmW frequencies make it difficult to optimally design a wireless system. Channel characteristics, including the properties of reflections at different materials, e.g. in indoor scenarios, influence the capabilities of waveforms, transceiver algorithms and beamforming and MIMO schemes. So, channel properties identified in Task 2.6 will be the second boundary condition, besides the hardware impairments of Task 2.2., which substantially influences the design of the other system components waveform, beamforming architecture and MIMO scheme extensions.

To identify a sound way forward towards reasonably realizable system designs, the gaps in hardware, and the hardware-related impacts identified for waveforms, beamforming and MIMO schemes have been initially assessed. In the following the major gaps and realization impacting facts are summarized in relation to the addressed use cases. Then the next steps towards solutions for upper mmW system design is described, highlighting the identified major topics of investigation. The idea is to fill the gaps as much as possible to reach the defined requirements, but also keep the energy efficiency targets in mind. Nevertheless, not all requirements might be met in this first attempt, and the final solution will be a trade-off between different design parameters.

4.1 Reducing Gaps Arising from Hardware Limitations

From hardware perspective the most obvious limitations are coming on transmitter side from the power amplifier and the associated IC process technologies. With increasing frequency, the achievable output power and the PA efficiency decreases due to limitations of the existing affordable IC processing technologies capable to support needed carrier frequencies of the 6G wireless systems. It is essential to avoid any losses between PA output and antenna, because this has direct impact on energy consumption, which need to be considered in the RF system architectures of the 6G radios. Parallelism of the radio architecture may reduce the needed output power from individual PA, but the physical size of the implementation may and will be problematic, if the RF architecture would utilize phased array approach with minimal performance degradation. It would be advantageous to use half wavelength separation between antenna radiators to reduce grating lobes of the array formation, but this will set straight physical size requirements for the radio path and power amplifier implementations. If high level of parallelism in the radio implementation can be achieved, then the output power per PA can be reduced and the antenna array gain may compensate individual PA output lower reduction and it may result in increased EIRP of the radio solution.

On the receiver side, we have major impacts from noise figure increasing with frequency of the first amplifier. This leads to reduced receiver sensitivity and reduced allowable path loss. Larger antenna gain or increase number of receiver antennas and associated receiver chain may compensate the path loss reduction due to noise level increase of the first amplifier compared to the lower frequency counterparts. However, this approach requires more active RF circuits and RFIC area, which leads higher implementation cost of the radio solution.

The frequency generation for mmW and THz frequency radios is not an easy task, since increased frequency will require more stable reference oscillators to ensure that the radio communication will occur at the intended radio channel. The generation of the local oscillator frequency is problematic and the usage of the multiplication of the reference frequency will lead to increased phase noise compared with the reference oscillator. Thus, the spectral purity of the reference oscillator will limit the performance of the 6G radio, and the technology of the reference oscillator will have utmost performance effect of the 6G radio. It should be noted that highest performance oscillators are big, bulky, and costly and thus those are not easy to implement and integrate into handheld device or small size radio base station.

The effect of the wide band noise due to LO signal generation may be partially compensated, and the related complexity needed for a reasonable performance, depends on the signal format. On the data converter devices the existing gaps do not primarily result from the high carrier frequency, but from the sampling rate related to the extreme signal bandwidths which are needed to achieve first wave 6G data rate of 100 Gbps and in future 1 Tbps, which is the ultimate goal of the 6G communication. Energy consumption is an issue in every block of the 6G radio implementation, but especially with data converters the energy consumption increases related to the communication signal bandwidth and the associated sampling rate and resolution of the converter.

The currently available radio architecture, hardware and the silicon technologies for mandatory RF blocks and components may provide proof-of-concept level implementations, but the mass production quality implementations with needed integration level and energy efficient implementations for base station radios and handheld devices with carrier frequencies up to 300 GHz and sampling rates of several tens of gigahertz are not short term available. If currently available technologies are combined for the 6G extreme data rate radio implementation, then the device properties and performance parameters are worse than current 5G implementations at lower frequencies and those are unfavourable with respect to the targeted system KPIs.

A way to overcome previously mentioned hardware gaps need to be solved on the 6G system and RF architectural level. Integrating available devices into a clever 6G system design, which allows to compensate for insufficient performance in an efficient way, would be an option. We can e.g. use larger antenna arrays to compensate for low output power, thinking about channelization and reduction of the needed RF bandwidth in individual signal path to reduce the noise and output power requirements, and select 6G waveforms, which are unsensitive to wide band phase noise or allowing for low complexity compensation of it. Of course, this comes with an additional power consumption, increased number of RF components and devices, higher computational and DSP complexity, but there is always a trade-off between performance and effort which need to be solved, and which need to be adapted to a specific use case.

Further, since technological progress is advancing, the availability of improved technology needs to be carefully monitored and new innovative design ideas need to be considered when a benefit in terms of performance, hardware effort and energy efficiency can be achieved.

4.2 Planned Work on Hardware-aware Waveforms

In Section 3.3.9 several KPIs for waveform have been formulated. The most relevant ones are power efficiency, robustness to hardware impairments, implementation complexity, out of band reduction capability and bandwidth scalability. Further, a set of waveform candidates has been initially assessed with respect to these KPIs, with classical OFDM as defined in the 3GPP 5G NR standard used as baseline. The waveforms under consideration are zero-crossing modulation with temporally oversampled 1-bit quantization, analogue multicarrier, DFTS-OFDM, SC-FDE, CPM-DFTS-OFDM and ceCPM.

With respect to the power efficiency KPI all waveforms are superior to OFDM. For ZXM, DFTS-OFDM and SC-FDE, possible room for improvement should be investigated. Robustness to hardware impairments is largely uninvestigated and should form a major part of the investigations in the scope of this project. Even for the relatively well studied DFTS-OFDM and SC-FDE, it is of interest to analyse the robustness to RF impairments at upper mmW frequencies using the impairment models for hardware operating in that specific frequency range.

Implementation complexity needs to be more investigated. Not only the waveform properties, but also implementation variants can impact complexity. The resulting performance-complexity trade-off, as well as trade-offs between all the important KPIs should be thoroughly investigated.

With respect to the KPIs OOB reduction capability, multiband operation capability and bandwidth scalability all candidate waveforms look remarkably well suited. An open point for all waveform candidates is the robustness to time- and frequency-selective channels. This needs further investigations at least for some of the more novel waveform candidates.

These observations should be used as basic guidelines in the investigations on waveforms suitable for operation in B5G/6G.

4.3 Next Steps on Hardware-aware Beamforming

The major impacts on beamforming given by the hardware constraints and channel conditions has been analysed in Section 3.5. To improve the link budget for an upper mmW system design, there is the need for providing high array gain to compensate high free space path loss, low PA output power at high frequencies and receiver noise figure and high noise floor due to the intended high bandwidth.

Different transceiver architectures need to be considered. The choice of using either analogue, hybrid or digital beamforming has not only impact on the number of simultaneously feasible MIMO streams and spatial multiplexing capabilities, but also on the energy efficiency. It depends on the channel conditions and use cases, to which extent a high flexibility of a digital beamforming can be exploited in practice and which architecture should be realistically applied. Main parameters from system design perspective are the number of RF chains and the ADC resolution.

From the hardware perspective the transceiver architecture is mainly defined by antenna types. For array antennas the geometry and size in terms of number of elements are the relevant parameters defining the gain. The location of the PAs within the RF part is essential for the energy efficiency but may depend on the used technology. For other antenna types, like lenses and reflector antennas, the beam switching, and gain adjustment is less flexible or even fixed.

Given a certain architecture, the study of beam forming, and steering approaches should consider adaptive beamforming for different degrees of freedom of parameter adaptation, e.g. continuous phase shifters, analogue, hybrid or digital beamforming, or beam selection from a grid of beams or a codebook. For that, the algorithm complexity and implementation feasibility are major properties to be considered.

To operate a system practically, the beam management techniques should be studied with respect to the different beam forming architectures. Main functionalities are beam search strategies for initial access, beam tracking or switching and beam alignment for use cases with mobility, and multiuser support via SDMA or FDMA / TDMA. For these functionalities, radar or sensing capabilities or localization data can possibly be exploited. Also, AI could be considered for predicting beam direction in mobility use cases.

Based on the studied schemes, the final goal of this task is to propose optimized designs that fulfil the link KPIs for the use cases with optimized trade off between low implementation complexity and high energy efficiency.

4.4 Next Steps on Distributed MIMO Systems

Distributed and collaborative MIMO schemes have shown to be an efficient means for increasing system capacity, flexibility, and scalability. Whereas for low frequency bands many MIMO schemes and ways of operation have been investigated, there are still gaps and uncertainties how to efficiently apply such schemes in lower and upper mmW bands. Reasons are the fact that MIMO systems in the lower mmW band were coming up only recently. In upper mmW band beyond 100 GHz the initial steps to understand the impacts of the different physical layer and device properties even have just started within the Hexa-X project. Besides these pure physical differences there are also new upcoming system architectures and use cases beneath the classical access, like e.g. IAB and mesh configurations, as well as cooperative MIMO schemes and user-centric AP clustering and load balancing. All these deployment types need to be investigated with respect to the gaps described in section 3.6.3, under the constraints implied by the targeted higher frequencies.

Next steps on distributed MIMO systems therefore will start with the evaluation of the potential and applicability of distributed and collaborative MIMO schemes to various backhaul/fronthaul architectures and mesh networks. A further aspect of the new architectures in combination with the expected transmission properties is the interference handling and dynamic blocking mitigation with help of advanced MIMO schemes. First, the lower mmW band, later the upper mmW band will be addressed. Research will consider performance evaluation of realistic deployment options, hardware impairments, scalability limitations and traffic requirements. In addition, the impact of different architectural and functional splits as well as resulting additional backhaul and control requirements will be assessed.

Finally, based on the results derived in the tasks T2.2, T2.3, T2.4 and T2.6, the potential and usefulness of the distributed MIMO schemes for the upper mmW band > 100 GHz will be assessed and needed adaptations and enhancements will be identified. So, whereas the other tasks of this work package mainly investigate physical layer aspects of individual topics and components, Task 2.5 will contribute with concepts how to combine the different components for use in the upper mmW band in a way to achieve best possible performance and efficiency for the relevant deployment scenarios.

4.5 Reducing the Channel Model Gap Through Sharing the Measured Channels – the Stored Channel Model

The contributions of Task 2.6 to the channel model gaps for above-100 GHz RF cover the development of a stored channel model and database of material permittivity for above-100 GHz.

The use of measured channel responses for physical layer design and evaluation on a computer has been a well-recognized approach, e.g., [MST+02], [KSM+05], as it allows repeatable tests and comparison of physical layer schemes. The fact that measured channel responses serve as the ground-truth of any simulation-based channel modelling also justifies the use for realistic evaluation of any radio systems. There are, however, also several drawbacks of using measured channels for physical layer studies, i.e., 1) measurements are always subject to uncertainties; 2) it is not straightforward to apply the measured channel responses to simulations that assume different hardware requirement than the measurement, e.g., signal dynamic range, antennas/arrays, system bandwidth and moving speed of a mobile; 3) a sufficient amount of measurements, e.g., for Monte-Carlo simulations and evaluation of packet error rates, may not be available due to limited capability of channel sounding. The measurements are moreover limited to certain environments where channel sounders can be installed; for example, it is not easy to perform Terahertz channel sounding for ground-to-unmanned aircraft scenario. There exists a need to overcome the aforementioned drawbacks by, e.g., i) properly performing calibration of the channel sounder and filtering noise from measured channels, ii) under-sampling or interpolating the measured channels in space, bandwidth and time and iii) by making a general mathematical framework that allows us to over-sample, extrapolate, or invent the measured reality, which is called a channel model. The approach ii) is exemplified by Molisch *et al.* [MST+02] where band-/aperture-/time-sampling-limited measurements of channels are approximated by the band-/aperture-/time-sampling unlimited form. The former, coming from calibrated measurements, is represented by power spectrum while the latter is a discrete model of propagation paths represented by Dirac delta functions. Figure 4-1 illustrates the band-/aperture-limited and band-/aperture-unlimited forms of 140 GHz indoor channels. It is possible to reproduce infinite amount of small-scale fading realizations from the propagation paths of channels by applying the uniform randomly distributed phases to each path before summing them up at the antenna. The uniformly distributed phase variation to each path is justified by a random local movement of a mobile terminal. The exact paper [MST+02] analyses the Ergodic channel capacity of MIMO channels from limited MIMO channel sounding, whereas Selimis et al. [SNL+21] uses the same approach to identify the most suitable fading distribution at 140 GHz.

In Task 2.6, channel response as a function of angles of arrival and departure, propagation delay, and a polarimetric amplitude of propagation path across antenna locations and time will be measured, depending on the capability of the channel sounder. Our goal is to establish an extensive stored channel model and to open them as an asset of the public as was already practiced, though in a limited scale, for 5 GHz MIMO channel sounding [IH19].

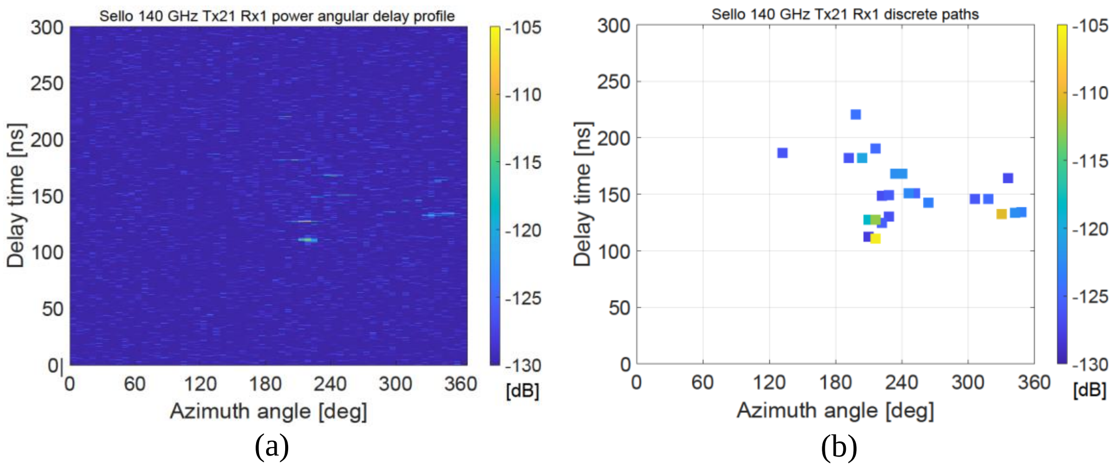


Figure 4-1: (a) Band- and aperture-limited channel response from a measurement and (b) its band- and aperture-unlimited model as propagation paths. Data are from a shopping mall measurement at 140 GHz [NJK+18].

4.6 Next Steps Summary

The design of high rate communication systems faces many challenges on different technical and technological areas, like hardware technology limitations, physical limitations of propagation, architectural and complexity issues. Under such constraints, the requirements of the identified use cases must be fulfilled. For that, various options of hardware architecture, realization and technology selection, waveforms and beamforming technologies and MIMO approaches are discussed, so that together with the impact of the channel a system design for each of the addressed use cases must be derived.

A prerequisite for that is the thorough investigation of the above mentioned components of the system, while respecting the specific requirements and boundary conditions of the use cases. In addition to the pure functionality a major concern is implementation complexity and energy efficiency, since initial investigations already showed an increased energy demand for large array sizes and high transmit output power.

In this deliverable, we identified and explained significant gaps between what we know and what we will need to achieve. This indicates that the next steps will have a twofold characteristic: on the one hand trying to fulfil the pure requirements may lead to a system approach, which is feasible, but either too complex or too energy inefficient or both. On the other hand, pushing the proposed hardware concepts, waveform, beamforming, and MIMO design under the given constraints in direction of the defined KPIs might not be sufficient to reach the goal.

Currently, the next planned steps of the project are based on this initial assessment of gaps and use case assumptions. We will address detailed investigation on the most important technical topics to approach the KPIs and find new solutions to overcome the remaining gaps. Special focus should be on a suitable architecture of the overall system, considering the specific properties of all the discussed components and their limitations. From the use case perspective, we will have to understand the details of the requirements and feasible trade-offs between the different KPIs, not to do overprovisioning in a highly limited environment. Ideally, the resulting solutions will be a compromise between efficiency, feasibility, and performance.

It is expected that further insights in the impacts of the upper mmW frequency, the technological progress and the evolution of use cases will lead to further adaptations of the requirements and the target KPIs, thus modifying the next steps accordingly. But starting with these currently identified next steps is a solid basis for successful system designs.

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Annex A: Terms and Definitions

Term	Definition
Communication Reliability	Ability to fulfil the communication requirements given additional constraints
Physical layer latency	Smallest physical layer time resource allocation granularity
sub-THz frequencies	The frequency range between 100 GHz and 300 GHz
x-haul	Unifyingly refers to fronthaul, midhaul and backhaul as known from cloud radio access network (C-RAN) architecture.