Hexa-X | WP2 | D2.1

Towards Tbps Communications in 6G: Use Cases and Gap Analysis

30.06.2021

Introduction

D2.1 provides gap analysis *towards achieving Tbps communications in 6G* from

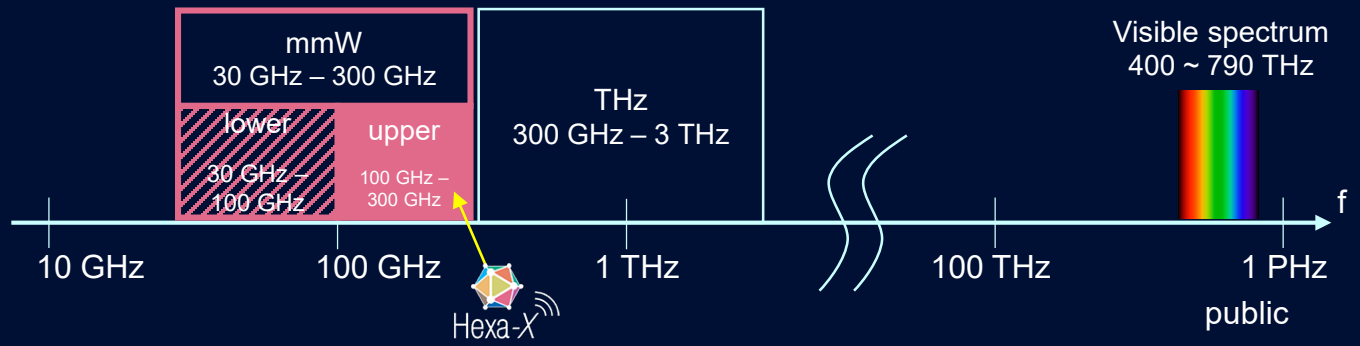
- Use cases
- Technology

perspectives.

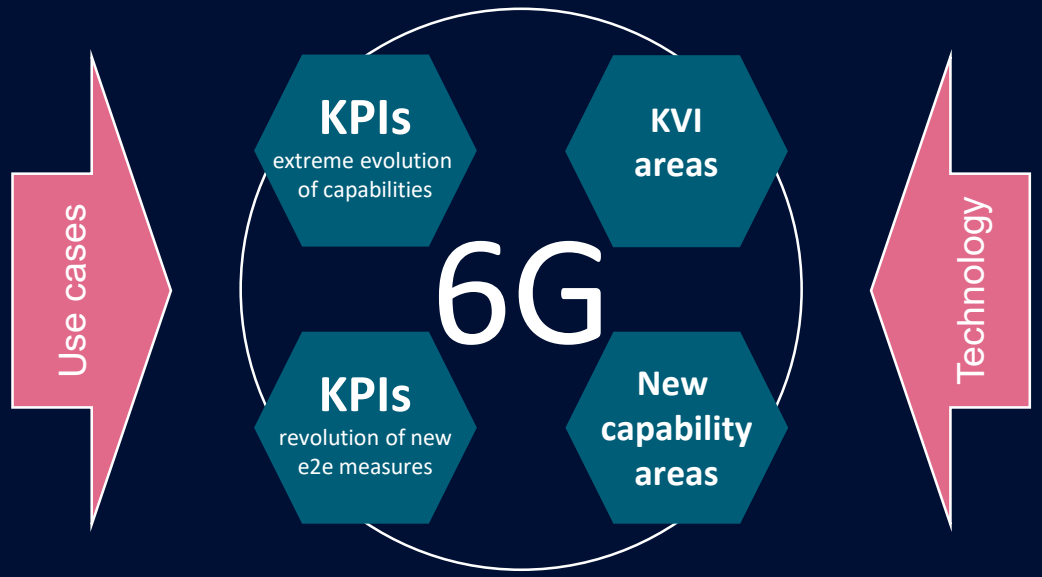
Considered technologies/solutions are:

- Hardware
- Waveforms
- Beamforming
- Distributed MIMO
- Channel models

WP2 is focused on exploring the upper mmW frequencies, while also considering improvements in the lower mmW range.



D2.1: Gap analysis from two perspectives



Classification of mmW technology by communications & sensing functions

6G mmW technology
(in upper & lower frequencies)

Short-range wireless links

Small cells & access points, <100m

- **Wireless access (D2I)**: **D2I** at short ranges with low mobility
- **Local networks (D2D)**: **D2D** to disseminate information locally

Long-range wireless links

Front-, mid-, back-haul

- **Fixed wireless links**: When laying **fibre** to extend the reach of wireless networks **is not convenient**
- **Mobile wireless links**: When at least one communication node is moving, **fibre is not possible**

Sensing w/ radio waves

Not “sensor networks”

- **Localization**: Devices obtain accurate location information about **own location**
- **Mapping, Tracking**: Capture the shape of the **environment** or objects/people
- **Spectroscopy**: **Interaction** of EM radiation **with matter**

Enablement potential of communications and sensing functions for 6G use cases (1)

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

For **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 (e.g., vehicle platoons)
- Enable dynamic wireless backhaul for local networks that need a communication link to connect to other network(s)

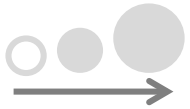
For **additional evolving use cases**:

- 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

Enablement potential of communications and sensing functions for 6G use cases (2)

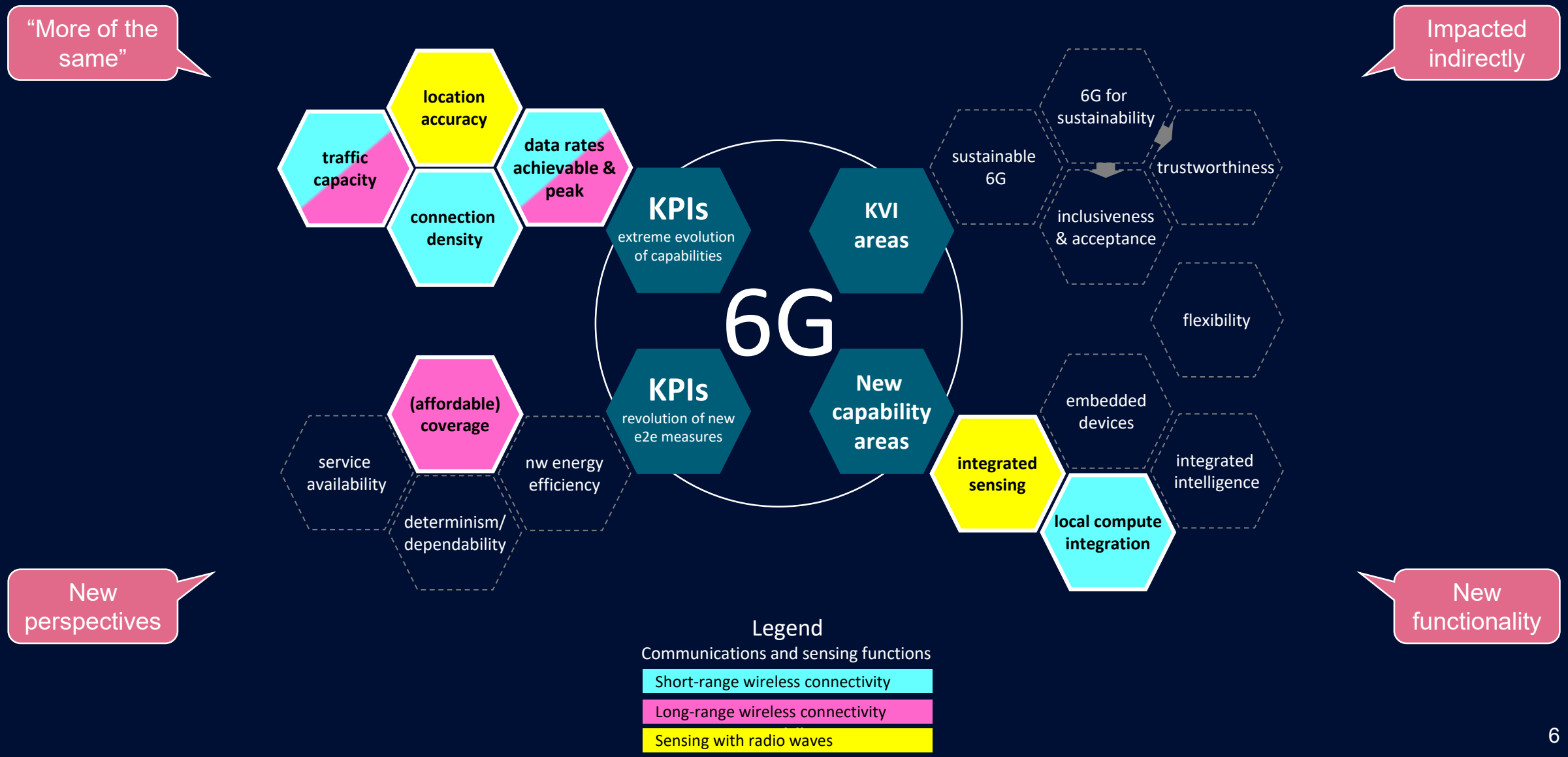
Legend

Potential for enable-ment of use cases by functional areas



Use case families	Sustainable development	Massive twinning	Telepresence	Robots to cobots	Local trust zones	Additional evolving use cases
Representative use cases	E-health for all	Immersive smart city	Fully-merged cyber-physical worlds	Interacting and cooperating mobile robots	Dynamic and trusted local connectivity	
Functional areas of mmW solutions						
Short-range wireless connectivity: Wireless access (D2I)	○	●	●	●	○	?
Short-range wireless connectivity: Local networks (D2D)	●	○	●	●	●	?
Long-range wireless connectvty: Fixed wireless links	○	●	●	●	●	?
Long-range wireless connectvty: Mobile wireless links	●	○	○	○	●	?
Sensing with radio waves: Localization	○	●	●	●	●	?
Sensing with radio waves: Mapping & Tracking	●	●	●	●	○	?
Sensing with radio waves: Spectroscopy	●	○	○	○	○	?

6G performance measures and capabilities primarily targetted by communications and sensing with mmW technology



Overview of Optical Wireless Communication

- OWC is complementary to RF technologies for the evolution of wireless systems
- R&D in OWC is not in scope of WP2
- Optical approaches will be considered in the architecture for flexible network of networks (WP5)

Optical wireless communication (OWC) technologies	
VLC	Visible light communication
LiFi	Light Fidelity
OCC	Optical camera communication
FSOC	Free space optical communication
LiDAR	Light detection and ranging

	Infrared (IR)	Visible light (VL)	Ultraviolet (UV)*
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

*UV is unsafe for humans & materials

Opportunities

- Privacy by design restricting signal availability in buildings
- Hotspot services in ultra-dense networks
- High-capacity backhauling
- Potential for wider bandwidths and higher data rates (IR + VL = 785 THz)
- Very low power consumption (except for UV spectrum), low-cost emitters with lighting equipment, lack of interference with any radio device and network

Challenges

- Interference from natural/other light sources makes VLC and LiFi not suitable for outdoor applications
- Atmospheric conditions (fog, haze and rain) have conspicuous impacts to the link reliability and performance of FSOC and LiDAR
- Frame rate of conventional image sensors limits the achievable data rate in OCC
- LoS is required to use IR and VL spectra
- UV spectrum is considered unsafe for humans and affects materials

OWC for Wireless Access

- simultaneous LOS communication and illumination
- short range communication (<10 m) in indoor
- deployment in electromagnetic-sensitive areas
- different security levels and advanced geofencing capabilities
- railway stations, airports, museums, shopping malls
- underwater communications

OWC for Mobile Wireless Backhaul

- 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
- FSOC may provide backhaul solutions for cellular networks, VLC, LiFi, OCC, and different types of airplane / ground / satellite connectivity

OWC for Localization and Sensing

- LiFi and VLC may provide geolocation services with cm-level resolution
- Very accurate cm-level indoor / outdoor localization is provided by OCC
- LiDAR is an optical remote sensing technology that finds the range of and/or other information about a distant target

Initial Technical Requirements for 6G Radio beyond 5G NR

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
Radio link range (d)	100 – 200 meters	10 – 100 meters
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.)

Main Considerations for Extremely High Data Rate Radio Links

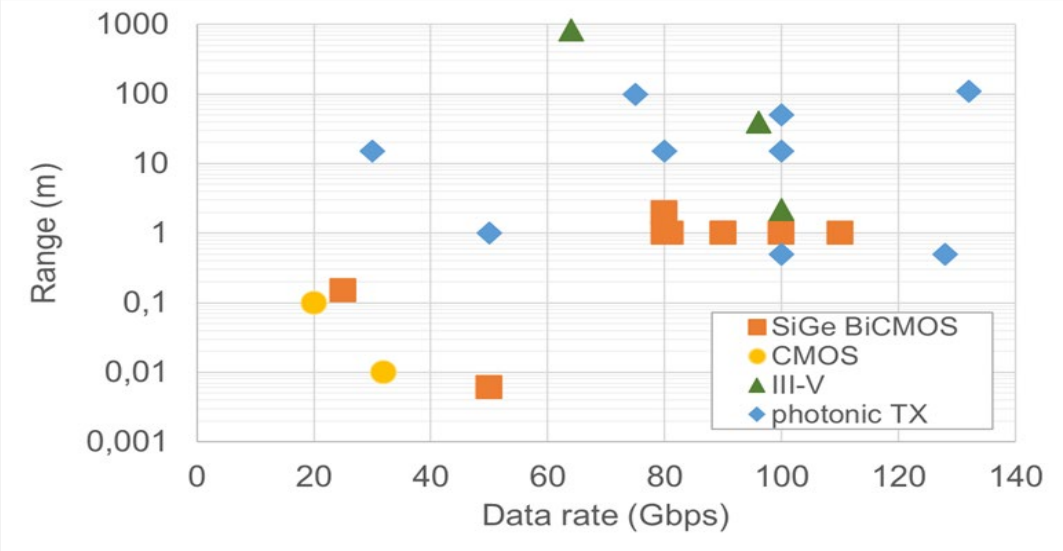
- **Extreme data rates enlarge needed bandwidth and thus operational frequency**

100 Gbps data rate signal bandwidth analysis

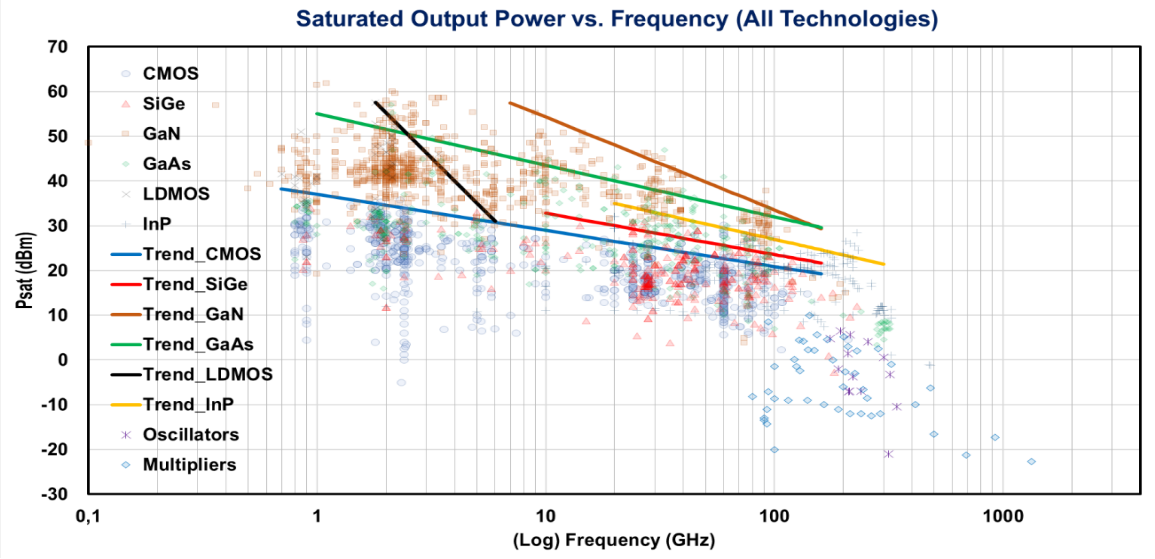
Modulation	bits / symbol (b/S), no coding	bits / symbol (b/S), 5/6 coding	RF BW no coding (GHz)	RF BW 5/6 coding (GHz)	BB BW no coding (GHz)	BB BW 5/6 coding (GHz)
BPSK	1	0.83	100.00	120.00	50.00	60.00
QPSK	2	1.67	50.00	60.00	25.00	30.00
16-QAM	4	3.33	25.00	30.00	12.50	15.00
64-QAM	6	5.00	16.67	20.00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

- **Recent PoCs have demonstrated data rates to 130 Gbps with limited link range without or with very limited mobility (no beam steering).**

SotA Link trials for very high data rates



- **Technological constraints will limit TX output power significantly at >100 GHz freq. compared to microwave or lower mmW adopted in 5G systems**

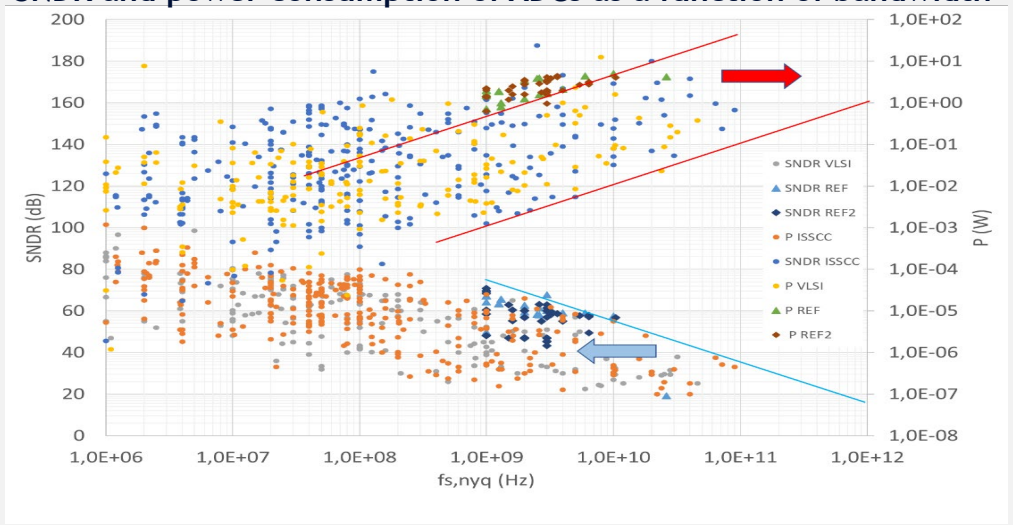


Hua Wang, et. al, "Power Amplifiers Performance Survey 2000-Present."

Other HW Related Gaps Based on Physics and Technology

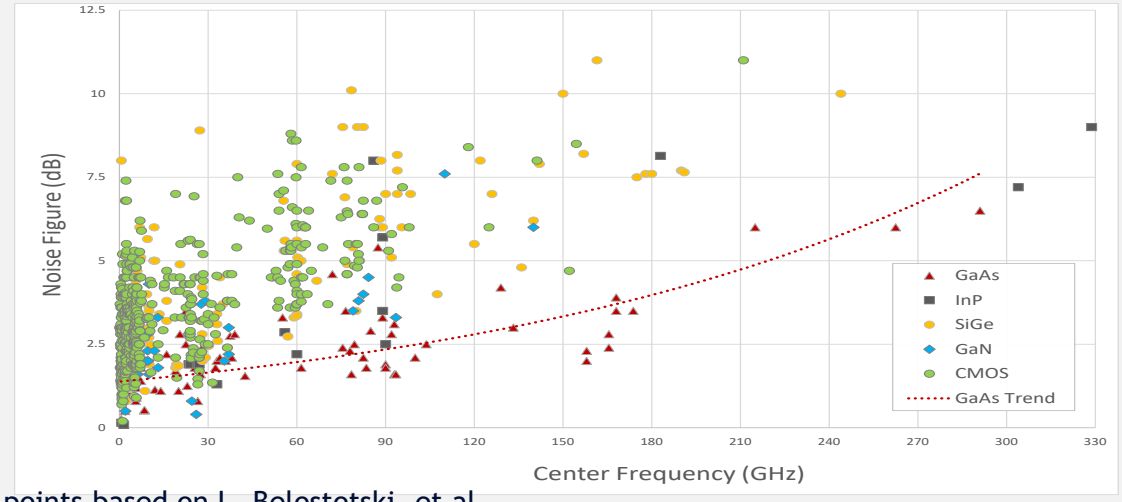
- Also noise figure of LNA raises with frequency
- Commercial ADCs consume substantially more power as complete systems compared to the best academic publications
- Physical size of the antenna radiator and separation between radiators have major impact on building phased arrays at upper mmW range with RF electronics

SNDR and power consumption of ADCs as a function of bandwidth



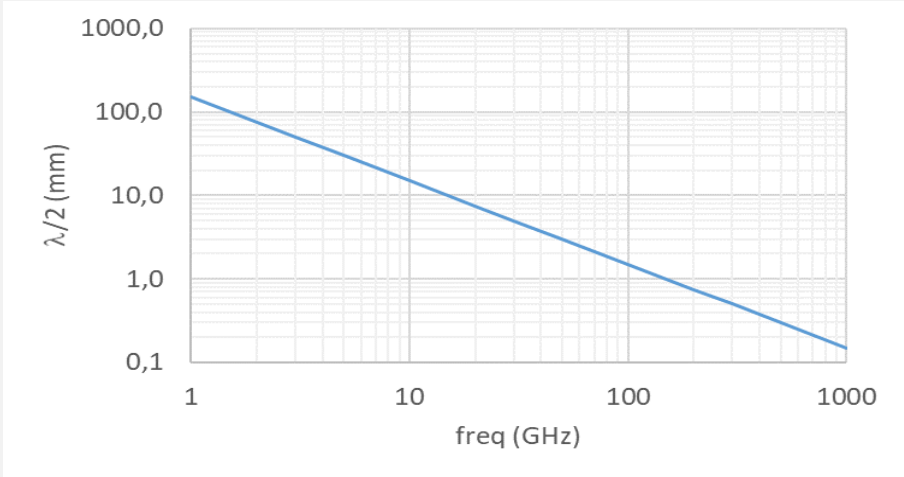
Adopted from B. Murmann, "ADC Performance Survey 1997-2020"

LNA noise figure vs centre operation frequency for commonly used semiconductor technologies



Data points based on L. Belostotski, et al., "Low-noise-amplifier (LNA) performance survey.

Typical antenna element distance (λ/2) in a phase array in mm as a function of frequency in GHz



Waveform Related Gaps – Candidate Waveforms

- Waveforms in B5G/6G will be designed primarily for high power efficiency (low PAPR), high robustness to HW impairments and low implementation complexity.
  - Motivation: high impact of HW impairments, large BWs, low peak PA power and efficiency, beamforming with narrow beams
- Chosen: a set of waveforms with promising prospects for offering good trade-off between design requirements
- Waveforms "graded" w.r.t. KPIs (with gaps implied, e.g. finding solutions to bring implementation complexity to low) and open problems identified:

KPI / Wave-form	PE	SE	Robust w.r.t. HW impairment	Cplx	Lat	MIMO compatibility	Freq. resource alloc. flexibility (multiuser)	Robust w.r.t. TS channels	Robust w.r.t. 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	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

KPI priority in context of B5G/6G:

= high

= medium

= low

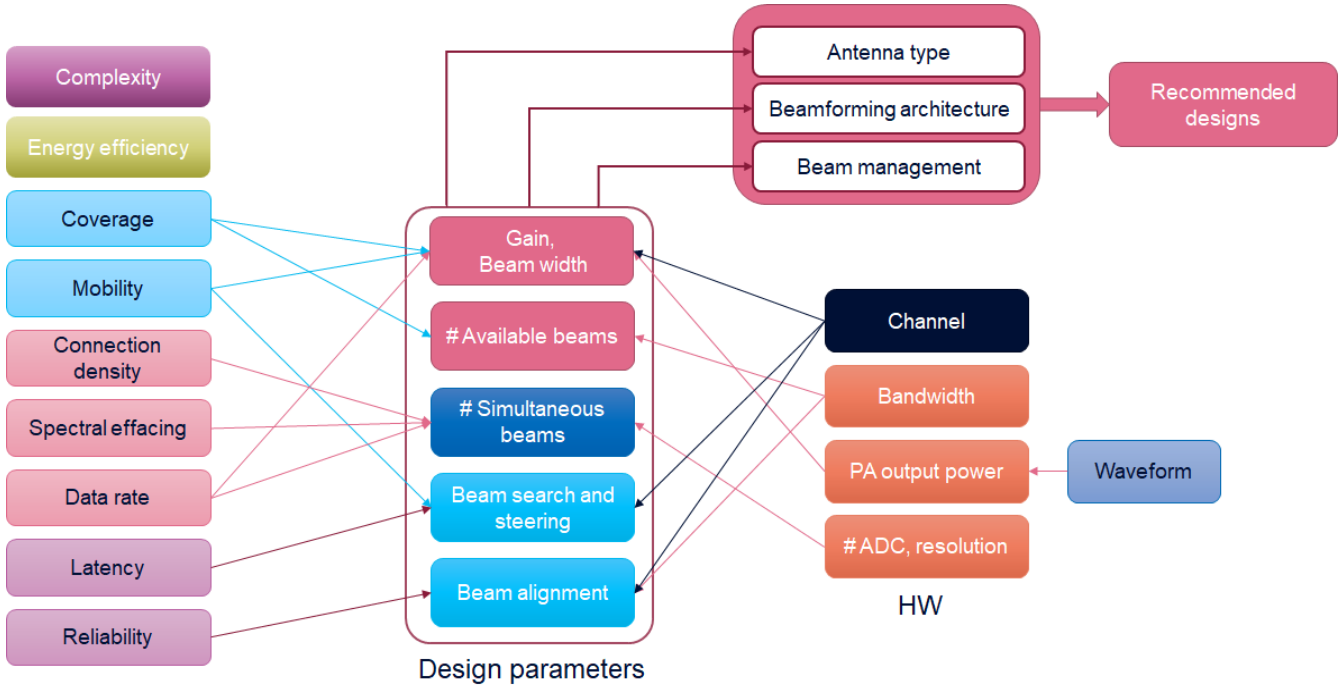
Waveform grade w.r.t KPI:
H = high M = medium L = low, O = open problem

PE = power efficiency, SE = spectral efficiency, Cplx = implementation complexity, Lat = latency, TS/FS = time/frequency selective, OOB = out-of-band

ZXM = Zero crossing modulation, DFTS = DFT-spread, SC-FDE = single carrier with frequency domain equalization, CPM = constant phase modulation, ce = constrained envelope

Beamforming Related Gaps

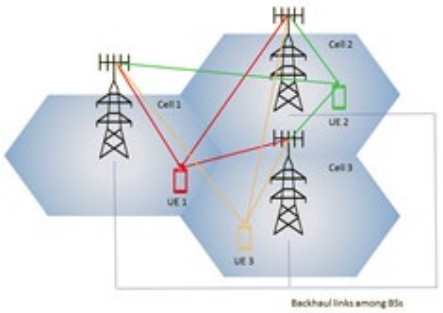
- **Hardware analysis, KPI requirements, and channel model determine the beamforming design parameters**
  - Antenna types: beam gain and width, number of available beams
  - Baseband chains: number of simultaneous beams
  - Types of beamforming: selection from a fixed codebook or adaptive (e.g. using phase shifters)
- **Based on the beamforming architecture, beam search, steering and alignment to be studied considering**
  - Very narrow beams
  - Latency
  - Mobility
  - Processing complexity

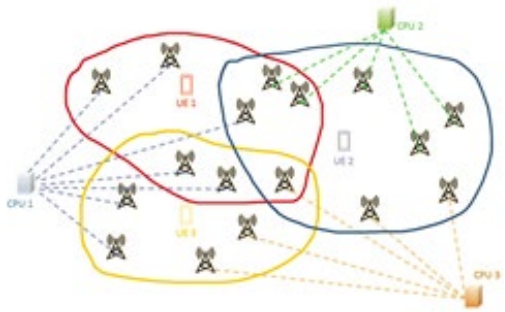


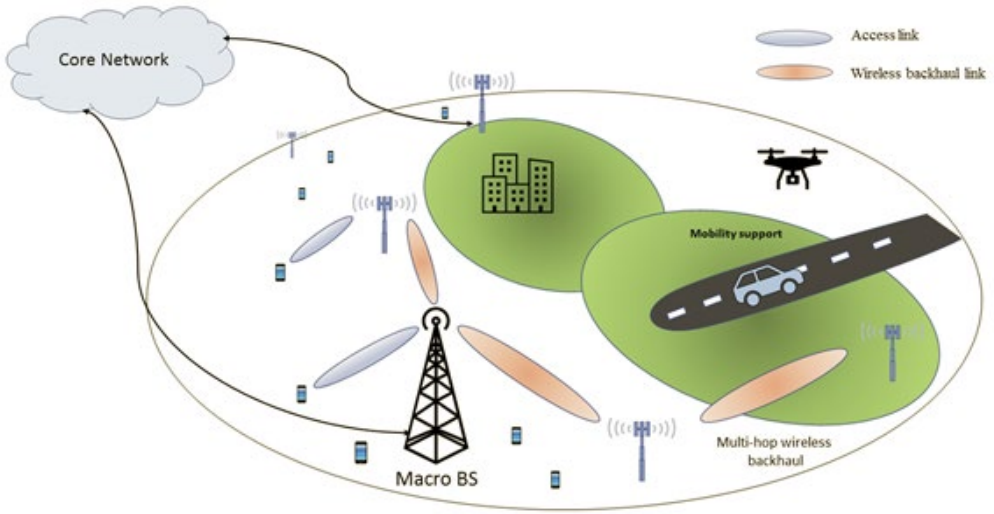
	Options	challenges
Antenna types	Reflector, lens, array	Size, number, integration
Beamforming architecture	Analogue, digital, hybrid, multiple fixed beams	ADCs, processing complexity, integration
Beam management	Codebook selection, adaptive, localization-assisted	Narrow beams, mobility, latency, processing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

Distributed MIMO Related Gaps

- **Investigate enabling techniques for scalable distributed large antenna systems with converged access-backhaul-fronthaul in beyond 5G/6G systems towards seemingly infinite network capacity for both below and above 100 GHz.**
  - Innovate and evaluate the performance of D-MIMO (cell-free) considering realistic deployment options, hardware impairments, traffic models and scalability limitations. Initial focus will be on lower mmW bands and moving above 100 GHz later.
  - Research will cover different architecture and functional split options on the communication layers, fronthaul trade-offs, integrated access, backhaul and fronthaul in mesh configurations, distributed hardware-aware precoding, user-centric, dynamic and scalable clustering and load balancing.







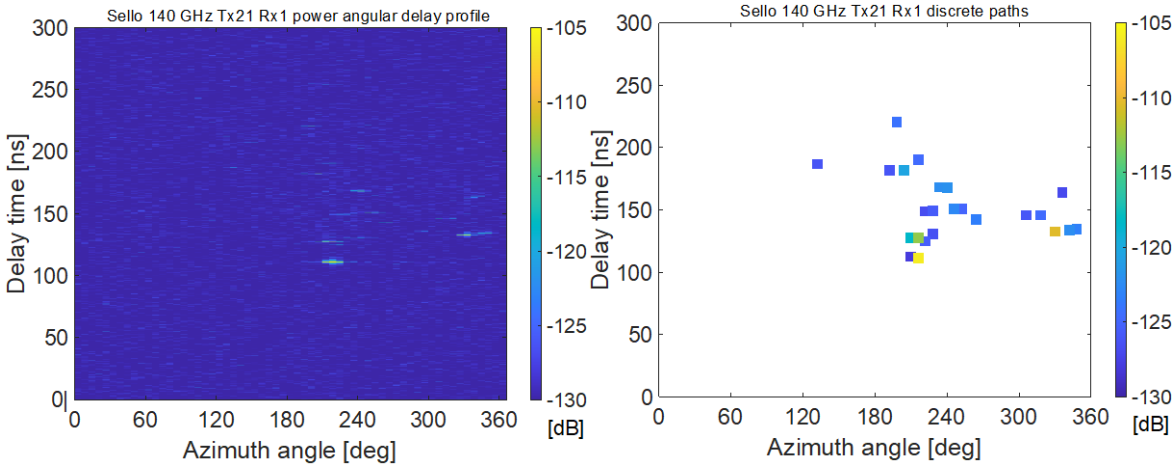
Channel Modelling Related Gaps for Upper mmWave, i.e., Above-100 GHz

- **Generally, in all aspects, experimental evidences are lacking as the ground-truth for any simulations and mathematical models.**
- **Gaps of knowledge in wave-material interaction.**
  - Permittivity and conductivity of common objects.
    - ITU-R recommendation values only defined up to 100 GHz.
    - Those physical parameters show continuous change across below- and above-100 GHz; but no measurement evidence.
  - Practical parameters: Radar cross section.
    - Simulations and measurements are limited to vegetation from remote sensing perspectives and human bodies.
  - Atmospheric losses: 1) fog and cloud attenuation at >200 GHz and 2) impact of rain drop size and shape.
- **Gaps of knowledge in multipath channel characteristics.**
  - Usage scenarios are not comprehensively covered, e.g., indoor, industrial and vehicular.
  - Small-scale (= multi-dimensional cluster properties) of wave propagation, esp. continuity between below-/above 100 GHz.
  - Understanding wave propagation mechanisms
    - Identification of physical objects in the environment producing multipaths: Are they specular or non-specular?
  - Site-specific channel modelling more relevant than fully stochastic channel modelling to, e.g., localization.

What Hexa-X does to address the gaps?

Stored channel model as referential ground-truth channel model

Example of measured data (= the stored channel model) from indoor measurement **<u>to be shared with Hexa-X partners</u>**.



Band-and antenna-aperture-limited measurements = continuous spectrum

Data processing

Band-and antenna-aperture-***<u>un</u>***limited form of the data ***<u>= discrete model</u>***

Summary & Outlook

- **The design of high rate communication systems faces many challenges on different technical and technological areas under**
  - Hardware technology limitations – scaling performance up over time not easy due to physics
  - Physical limitations of propagation - upper mmW channel properties not well known yet
  - Architectural and complexity issues
  - Energy consumption concern – spectral efficiency vs energy efficiency trade-off
  - All of these are strongly interrelated and forming tradeoffs in system performance
  - Novel approaches needed from components to platform architectures
- **With initially identified gaps, the next steps will have a twofold characteristic**
  - A top-down system approach to fulfill pure requirements from use cases
  - A bottom-up approach pushing the proposed hardware concepts, waveform, beamforming, and MIMO design under the given constraints in direction of the targeted KPIs
- **WP2 will continue to work on**
  - Understanding impacts of the upper mmW frequency
  - Developing enabling technologies and concepts
  - Carrying on estimating required KPI's based on anticipated use cases

HEXA-X.EU

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