Introduction

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

- Use cases
- Technology

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

**Long-range wireless links**
- Front-, mid-, back-haul
- **Fixed wireless links**
- **Mobile wireless links**
  - When laying fibre to extend the reach of wireless networks is not convenient
  - When at least one communication node is moving, fibre is not possible

**Sensing w/ radio waves**
- Not “sensor networks”
- **Localization**
- **Mapping, Tracking**
- **Spectroscopy**
  - Devices obtain accurate location information about own location
  - Interaction of EM radiation with matter
  - Capture the shape of the environment or objects/people
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)

<table>
<thead>
<tr>
<th>Functional areas of mmW solutions</th>
<th>Short-range wireless connectivity</th>
<th>Long-range wireless connectivity</th>
<th>Sensing with radio waves</th>
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<tr>
<td></td>
<td>Wireless access (D2I)</td>
<td>Fixed wireless links</td>
<td>Localization</td>
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<td>Local networks (D2D)</td>
<td>Mobile wireless links</td>
<td>Mapping &amp; Tracking</td>
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<td>Spectroscopy</td>
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<th>Use case families</th>
<th>E-health for all</th>
<th>Immersive smart city</th>
<th>Fully-merged cyber-physical worlds</th>
<th>Interacting and cooperating mobile robots</th>
<th>Dynamic and trusted local connectivity</th>
<th>Additional evolving use cases</th>
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Legend
Potential for enablement of use cases by functional areas

- ○: Significant potential
- ●: Low potential
6G performance measures and capabilities primarily targeted by communications and sensing with mmW technology

"More of the same"

New perspectives

Impacted indirectly

Legend
Communications and sensing functions
- Short-range wireless connectivity
- Long-range wireless connectivity
- Sensing with radio waves

KPIs
- extreme evolution of capabilities
- revolution of new e2e measures

KVI areas
- sustainable 6G
- inclusiveness & acceptance
- flexibility
- embedded devices
- integrated intelligence
- local compute integration
- integrated sensing

New capability areas
- service availability
- determinism/dependability
- nw energy efficiency
- (affordable) coverage

6G
- traffic capacity
- connection density
- location accuracy
- data rates achievable & peak

KPIs
- data rates
- nw energy efficiency
- energy (affordable)
- connection density
- location accuracy
- traffic capacity
- data rates achievable & peak
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)

<table>
<thead>
<tr>
<th>Optical wireless communication (OWC) technologies</th>
<th>Infrared (IR)</th>
<th>Visible light (VL)</th>
<th>Ultraviolet (UV)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLC</td>
<td>0.1 mm - 760 nm</td>
<td>760 nm - 380 nm</td>
<td>380 nm - 10 nm</td>
</tr>
<tr>
<td>LiFi</td>
<td>3 THz - 394.7 THz</td>
<td>394.7 THz - 789.5 THz</td>
<td>789.5 THz - 30 THz</td>
</tr>
<tr>
<td>OCC</td>
<td>LiFi, OCC, FSOC, LiDAR</td>
<td>VLC, LiFi, OCC, FSOC, LiDAR</td>
<td>LiFi, FSOC</td>
</tr>
<tr>
<td>FSOC</td>
<td>Free space optical communication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiDAR</td>
<td>Light detection and ranging</td>
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</tr>
</tbody>
</table>

**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

**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

*UV is unsafe for humans & materials
# Initial Technical Requirements for 6G Radio beyond 5G NR

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

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

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

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

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.

SNDR and power consumption of ADCs as a function of bandwidth

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

Typical antenna element distance (\(\lambda/2\)) 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:

<table>
<thead>
<tr>
<th>KPI Waveform</th>
<th>PE SE</th>
<th>Robust w.r.t. HW impairment</th>
<th>Cplx Lat</th>
<th>MIMO compatibility</th>
<th>Freq. resource alloc. flexibility (multiuser)</th>
<th>Robust w.r.t. TS channels</th>
<th>Robust w.r.t. FS channels</th>
<th>OOB reduction capability (single user)</th>
<th>Multiband capability (single user)</th>
<th>BW scaling</th>
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<tbody>
<tr>
<td>OFDM</td>
<td>M/L</td>
<td>H</td>
<td>M/H</td>
<td>M/L</td>
<td>H</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>M</td>
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<tr>
<td>ZXM</td>
<td>M</td>
<td>M/L</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td>O</td>
<td>O</td>
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<td>Analogue MC</td>
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<td>L</td>
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<td>H</td>
<td>H</td>
<td>H</td>
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<tr>
<td>DFTS-OFDM</td>
<td>M/H</td>
<td>M/L</td>
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<td>SC-FDE</td>
<td>M/H</td>
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<tr>
<td>CPM-DFTS-OFDM</td>
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<td>O</td>
<td>M/H</td>
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<td>ceCPM</td>
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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 and Challenges

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<thead>
<tr>
<th></th>
<th>Options</th>
<th>Challenges</th>
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<tbody>
<tr>
<td><strong>Antenna types</strong></td>
<td>Reflector, lens, array</td>
<td>Size, number, integration</td>
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<tr>
<td><strong>Beamforming architecture</strong></td>
<td>Analogue, digital, hybrid, multiple fixed beams</td>
<td>ADCs, processing complexity, integration</td>
</tr>
<tr>
<td><strong>Beam management</strong></td>
<td>Codebook selection, adaptive, localization-assisted</td>
<td>Narrow beams, mobility, latency, processing complexity</td>
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</table>
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 to be shared with Hexa-X partners.
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