Partners: AAU, EAB, IMEC, LMF, NXP, OUL, QLC, SAT, SEQ, SON, UBW, WIN

HEXA-X-II D5.2 Deliverable

Characteristics and classification of 6G device classes

Hexa-X-II

hexa-x-ii.eu

2023-10-31

Scope and objective

Main contribution of D5.2:
Classify the new device types and associated radio requirements, along with technological enablers, beyond current 5G devices to be addressed specifically in 6G

D5.2 addresses WPO5.1

Hexa-X-II WP5 objective WPO5.1:
Classify the new device types and associated radio requirements, along with technological enablers, beyond current 5G devices to be addressed specifically in 6G.

WPO5.1 contributes to Hexa-X-II Obj 3

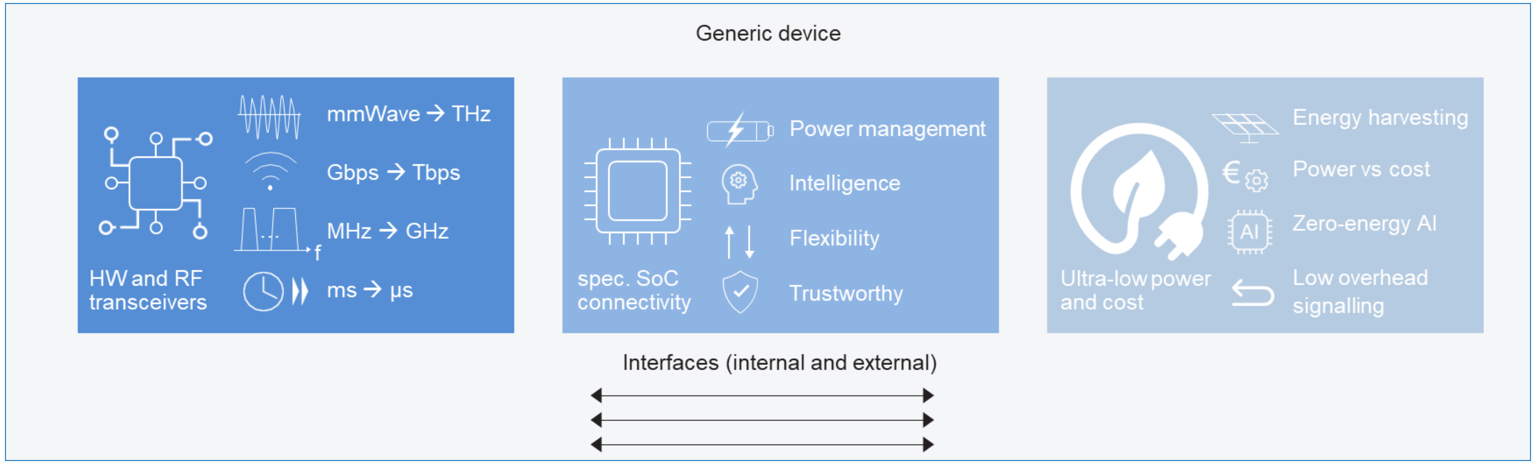
Hexa-X-II Objective 3:
Develop and describe radio access solutions for communication considering the requirements on 6G services

Key Definition

What is a device?

- D5.2 deliverable defines a device specifically as an end-device that is connected to the network infrastructure via a radio interface and which generates and/or consumes data (i.e., that runs an application) and shall be uniquely identifiable in the 6G system.

- As shown in figure below, the considered device consists of RF transceiver circuitry, a System-on-Chip (including a CPU, memory, and peripherals), and the necessary firmware and software.



Methodology

- The Hexa-X-II use-cases as described in Hexa-X-II D1.1 complemented with similar ones described in Hexa-X project such as Hexa-X D1.2, Hexa-X D1.3 and Hexa-X D1.4 are analyzed to extract the key device types and understand the deployment scenarios in which they operate along with the KPIs.
    - This was complemented with inputs from partners and other reference material to make the input analysis more comprehensive.

- With the characterization criteria, distinct device classes are identified with some key characteristics along with minor variations, assumptions and technology or infrastructure enablers.

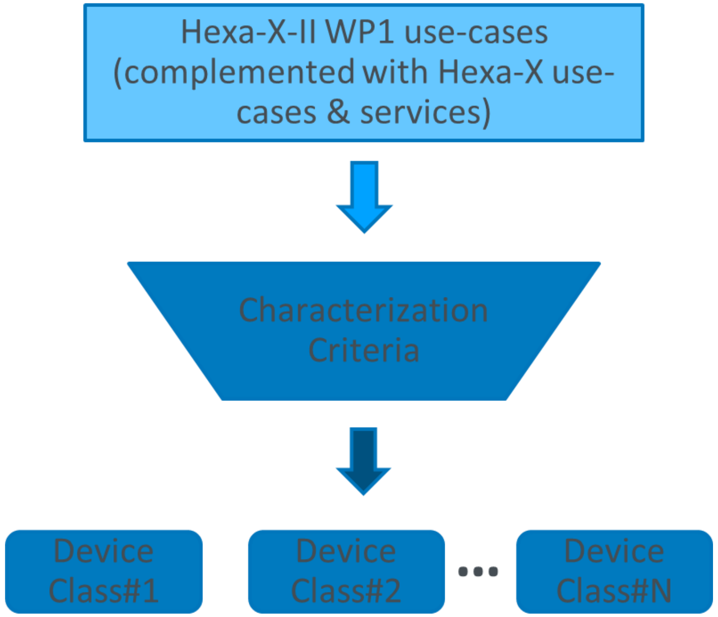
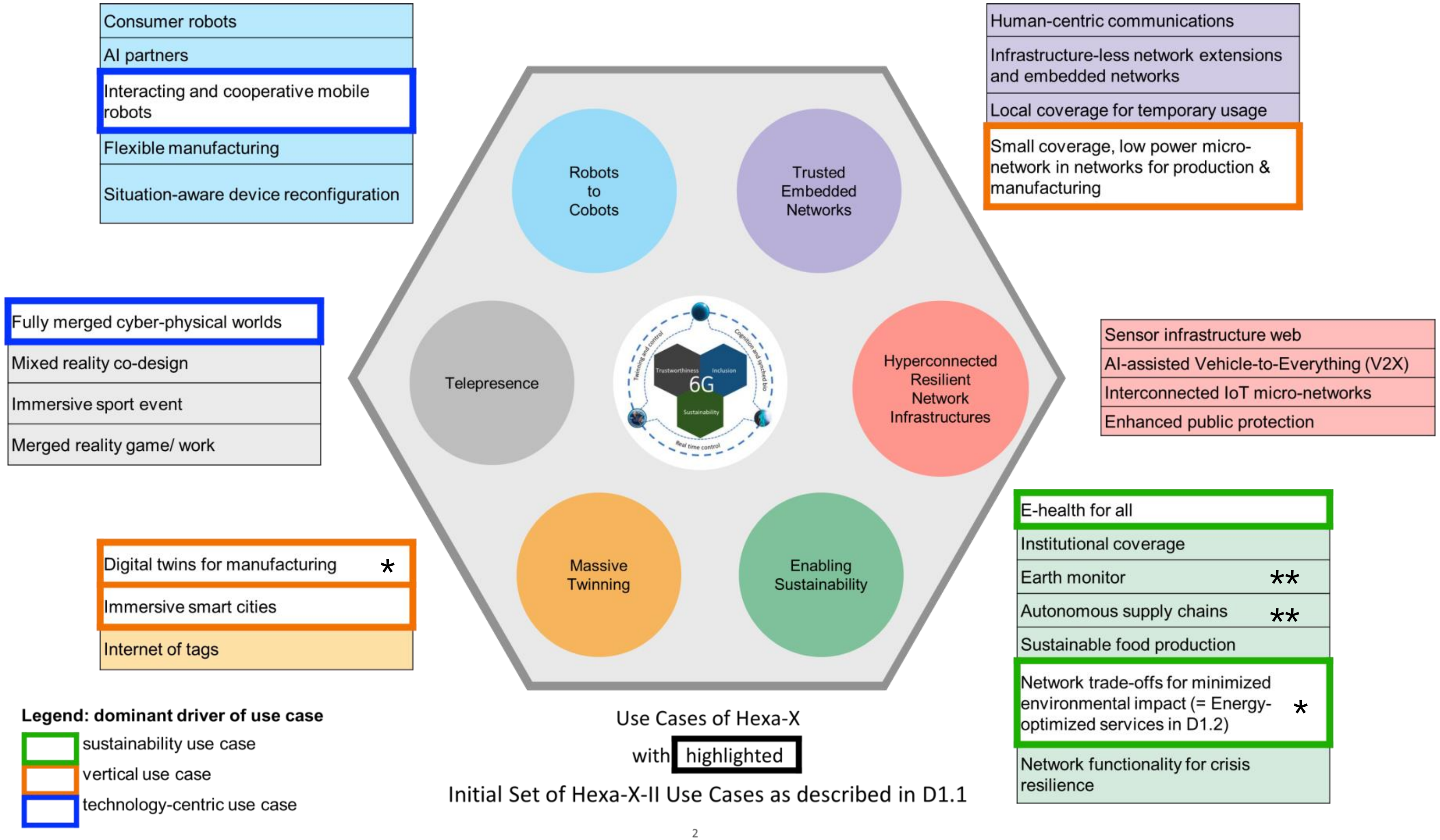


Table of Content: Main Chapters

Chapter 2

Use-case & services analysis and take aways

Hexa-X-II D1.1 Use cases overview



Note: From the initial set of Hexa-X-II use-cases, when analyzing use-cases in D5.2, * are not considered but ** are analyzed instead, to have a representative from all device categories.

Use-cases & services analyzed in D5.2

Use-case
E-health for all
Earth monitoring
Autonomous supply chains.
Fully merged cyber-physical worlds
Immersive smart city
Small coverage, low power micro-network in networks for production & manufacturing
Interactive and cooperating mobile robots

Services
Compute-as-a-Service (CaaS)
Situation aware device reconfiguration

Chapter 3

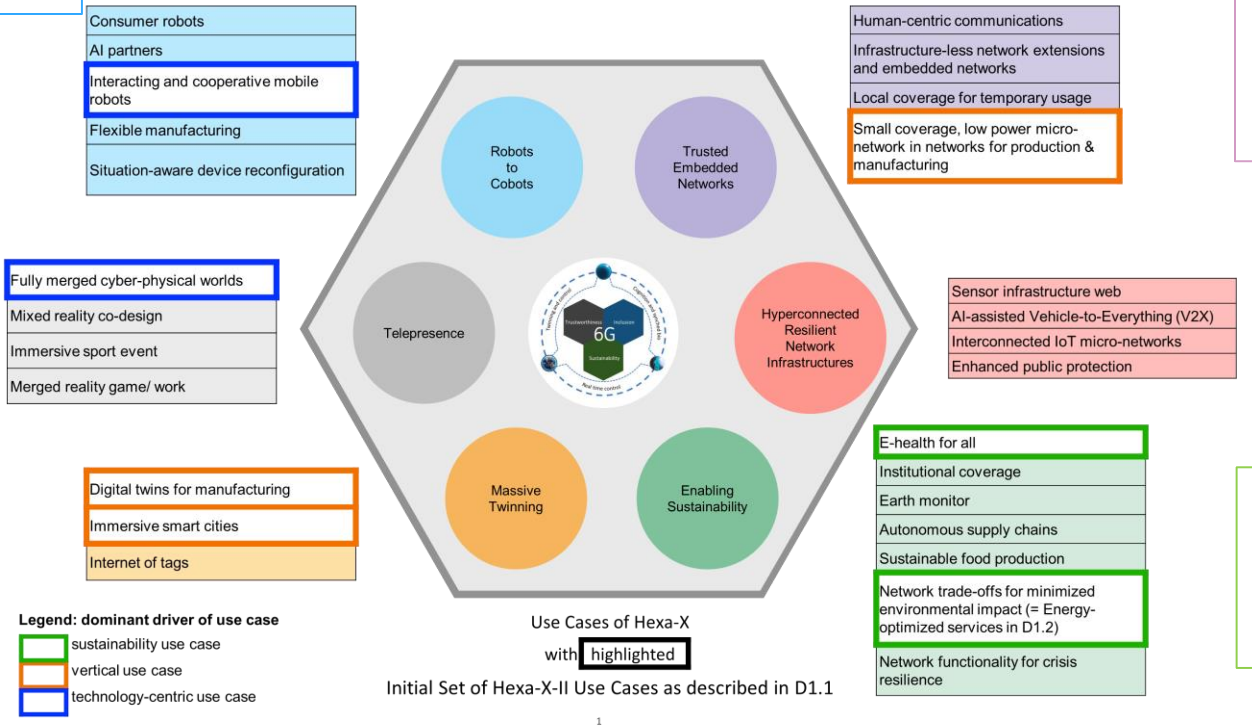
Characterization Criteria and Summary of sustainability guidelines

Use-cases and some example (new) devices realizing them

- Cobot (IoT/M2M)
- Mix of URLLC and eMBB services device

- (Reliable & available) XR devices
- On-body sensors and actuators + connectivity hubs….

- Zero energy devices
- (bio-friendly) Tags, zero e-Waste IoT



Use Cases of Hexa-X with highlighted

Initial Set of Hexa-X-II Use Cases as described in D1.1

1

- Resilient/available IoT devices
- Trustworthy/intelligent aggregator devices

- IoT devices

- Implantable devices
- Zero energy devices
- (bio-friendly) Tags, zero e-Waste IoT

- Main takeaways:
  - One device might serve multiple use-cases and have suitable implementation/design adaptations for specific use-case
  - Multiple devices are often needed to realize a single use-case.

Characterization Criteria

- Characterization criteria sets the basis to understand if the different devices in the 6G timeframe fall into a one device class or another.
- There are numerous characteristics concerning a device, such as its energy consumption, operating spectrum, authentication etc.
- The related characteristics are grouped, and the group name is indicated in the column titled "Group".
- The granularity is set at a coarse level to serve as a guide and depending on the exact implementation etc., it is possible that there are some sub-levels of devices which depict same or very similar high-level characteristics.

Group	Characteristic
Energy	Energy source
	Energy storage
	Energy consumption during (1) operation (2) idle/sleep
Lifetime	Device lifetime
Mobility	Device mobility

Group	Characteristic
Communication	Authentication
	Synchronization
	Time aware system component
	Spectrum
	Traffic flow
	Data rate
	Latency
	Reliability
	Availability
	NTN support

Group	Characteristic
AI & computation	Computation capability
Localization & sensing	Location accuracy
	Orientation accuracy
	Localization/sensing latency
Security	Security capability

Sustainability guidelines for 6G design

In Hexa-X-II, the following three sustainability types are to be considered in 6G design.

Note: While the characterization criteria outlined in previous slide help to determine different device classes; these device classes will also indicate the sustainability considerations along these similar lines that capture the key aspects that are to be considered during device design.

Environmental sustainability

- Holistic footprint approach
- Alternative materials
- Modular and durable equipment
- Energy Efficiency
- Cloud Computing and Automation
- Circularity practices

Social sustainability

- Cyber-secure and respect end-users privacy;
- Transparent AI-based approaches and keep the human in the loop
- Flexible and adjustable capacity and coverage
- Non-discriminatory, e.g., take into account IT literacy and culture of all types of end-users
- Ensure coverage and capacity at certain level.

Economic sustainability

- Value-based 6G design
- Sustainable 6G business model innovation
- Open value configurations via 6G
- Sustainable competitive advantage via correlated/holistic sustainability perspective in 6G
- Monetizing with 6G in challenging business environment
- Preparing for mitigating risks with 6G

Reference: HEXA-X-II D1.1

Chapter 4

Device classes

Device Class overview

From the use-case analysis and applying characterization criteria, D5.2 arrives at the following four device classes (and distinguishing them using some key criteria) and is summarized in the Table below. Among the groups of characterization criteria, we attached more weight to ones from energy and communication/radio performance to determine distinct device classes. This gives a good overview of the parameters that impact the energy and (radio) performance of the end-to-end system.

Further analysis is planned based on the upcoming deliverable on updated HEXA-X-II use-cases & associated KPIs and outlook for other new device classes or potential ones influencing these are mentioned in conclusions section. The result of analysis will be part of later WP5 deliverable.

Device class name → / Criteria	Energy Neutral (EN) device class	Reliable High Data Rate with Bounded latency (RHDRBL) device class	High Reliability & Low Latency (HRLL) device class	Enhancements of mMTC (EmMTC) device class.
Energy	During operation, Energy neutral (very low energy consumption)	Low energy (low energy consumption could take precedence over reliability)	Low energy consumption as possible (without compromising on reliability)	Low energy consumption
Data rate	Very low	High	Medium	Low
Latency	No mandatory requirements	Bounded latency	Low latency	No mandatory requirements
Reliability	No mandatory requirements	Medium	High	Low
Availability	No mandatory requirements	Medium	High	Low

Note 1: Relative indications (very low – low – medium – high - ultra) are used in this table to depict the distinction between the device classes. Some indicative numbers are available in Chapter 4 introduction & within the respective device class sections and depends on the specific deployments. This is planned to further refined in upcoming deliverables from WP5 based on KPIs from WP1.
Note 2: Zero energy devices, a device type that was identified in the use-case section are mapped into Energy neutral device class.

Individual Device classes

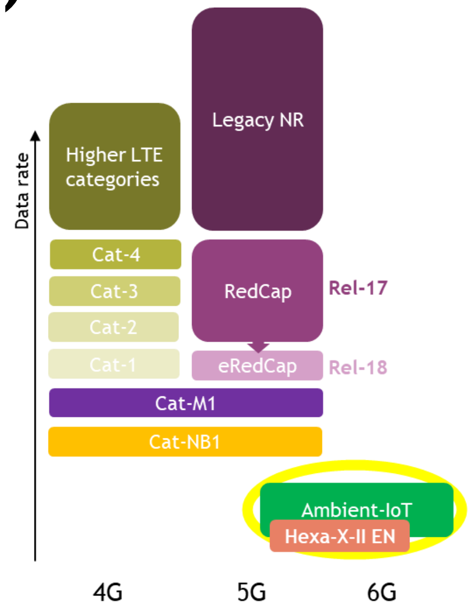
The following details on each of the identified device classes are covered in Chapter 4 sub-sections.

- Key characteristics that distinguishes it from any other device class (e.g., operates only on harvested energy)
- Other characteristics that are similar to another device class (e.g., low data rate that both EN and IoT sensors have in common)
- Technology enablers (technologies that help to realize devices within that device class).
- System / infrastructure enablers (if any) that will support the devices to be integrated in a 6G system
- Sustainability considerations that could be relevant to a class of devices is also described.
- A link to the use cases for each device class
- Examples of devices that belong to a specific class of devices are provided.

Note: where possible to have consistent numbers backed with references, the key performance parameters are detailed with these numbers.

Device class #1: Energy Neutral (EN) devices (1/2)

Energy Neutral devices: IoT device powered by energy harvesting that embodies an ultra-low energy consumption and demand throughout its entire life-cycle, facilitates zero waste generation, and embraces material circularity principles.



Key characteristics:
- Energy-neutral operation (energy storage and energy harvesting from sources according to the specific use case)
- Small form factor
- Extremely low cost
- Energy self-sustained
- Low mobility
- Very low data rate
- Predefined reliability/availability support levels (mostly low)
- Lifetime is use-case dependent (from a few months up to many years)

Technology Enablers:
- Low-overhead/signaling and energy-aware protocols
- Low-cost, circular, and/or biodegradable manufacturing technologies
- Backscattering
- Energy management
- Computation offloading
- Intermittent computing
- Wake-up radio
- Tiny ML

Note: Technology enablers are use-case dependent and subject to device capability.

Other characteristics:
- No tight synchronization and flexibility to support low-accuracy receivers.
- Security by 6G core networks. Additional low-complex 6G RAN security may be compounded depending on solution and RAT type.
- Wide coverage (especially for active EN devices)
- Primarily, licensed low spectrum bands.
- Simple waveforms, preferably compatible with OFDM.

Device class #1: Energy Neutral (EN) devices (2/2)

System/infrastructure Enablers
- Helper node
- RF-WPT

Sustainability considerations
- Environmental: Renewable energy sources and biodegradable or recyclable materials
- Social: Digital inclusion and well-being by enhanced wearable and in/on-body sensor and corresponding services, safety/security measures under environmental or security hazard, data privacy preserving capabilities.
- Economy (Optimizing resource usage and efficiency)

Key performance parameters
- Ultra-low energy consumption
- Highly efficient energy harvesting
- Low energy consumption per successful transmission

Link to use-cases
- Asset tracking, transportation & logistics
- Warehouse
- Industrial (factory automation, harbors, docks)
- Stores (automatic inventory etc.)
- Smart home

Example devices
- Tags
- Stickers
- In- or on-body sensors

Device class #2: Reliable High Data Rate with Bounded latency (RHDRBL) devices (1/2)

Reliable High Data Rate with Bounded latency devices : The reliable high data rate with bounded latency device class provides immersive experience, through mixed reality, augmented reality and virtual reality. With high required data rate, reliability and bounded latency demands, it ensures quasi-realistic virtual experience for merging cyber and physical worlds.

Key characteristics:

- Immersiveness and Presence: Presence is the feeling of being physically and spatially located in an environment.
- Presence is divided into 2 types:
  - Cognitive presence is the presence of one's mind. It can be achieved by watching a compelling film or reading an engaging book.
  - Perceptive presence is the presence of one's senses. To accomplish perceptive presence, one's senses, sights, sound, touch, and smell, must be tricked.

Other characteristics:

- Strict QoS requirements
- Multiple quasi-periodic DL and UL flows
- Computation :
  - Standalone
  - Direct link to NW
  - Link to NW via an (intelligent) aggregator/companion device

Technology Enablers:

- AI as a service: there are two crucial types of intelligence required to ensure effective and efficient performance: service intelligence and operational intelligence.
- Perception: facilitate enhance device awareness by applying inferencing methods applied to a collection of sensor and wearable data.
- Spectrum: utilize FR1, FR2, and potentially operate also in centimetric range and sub-THz bands for different objectives (capacity/coverage, data rate, etc.)

System/infrastructure Enablers:

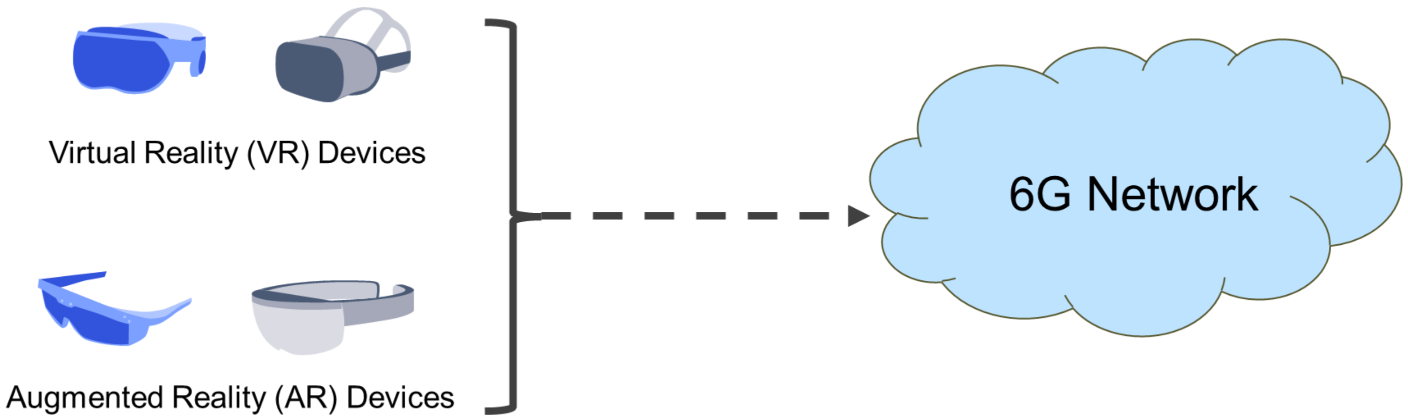
- Compute as a service: leverage computing power from the edge compute servers for graphics rendering for example.

Note: Technology enablers are use-case dependent.

Device class #2: Reliable High Data Rate with Bounded latency (RHDRBL) devices (2/2)

Sustainability considerations
- Environmental sustainability: enhances the collaborative work environments which can in turn reduce the need to vehicular mobility/traveling and thus, can be seen as an efficient way to reduce energy-related CO_2 emissions (“climate action”).
- Social sustainability: virtual medical consultations/educational classes can improve the access to healthcare/education and removes the distance barriers between the patients/students and the doctors/teachers (“access to quality health-care services” - “access to education”),
- Economic sustainability: facilitate socializing with family and friends and thus reducing the need for traveling and increase the possibility to experience other countries more often without traveling there (“sustainable tourism”).

Key performance parameters
- Data rate: 1 Gbps DL - 0.1 Gbps UL
- Latency: < 20 ms
- Availability: 99 %
- Reliability: 99.9 %



Link to use-cases
- This device class is the main enabling devices in fully merged cyber physical worlds use case (XR devices).
- It operates together with other body sensors/actuators (tactile gloves, electromyography (EMG) wristbands, smart watches, smart fabrics, etc.).

Example devices
- Augmented Reality (AR)
- Virtual Reality (VR)

Device class #3: High Reliability & Low Latency (HRLL) devices (1/2)

High Reliability & Low Latency devices : The highly reliable low latency device class combines seamless connectivity, autonomous operation, and safety for human collaboration. With stringent latency demands, it excels in real-time decision-making. This class supports diverse communication needs, energy efficiency, and interoperability, ensuring seamless integration with various devices.

Key characteristics:
- Reliability: Seamless connectivity and communication capability
- Autonomy: Adaptable and operate in diverse environment
- Safety: Responsive collaboration with humans
- Location awareness: Devices with contextual spatial awareness
- Low latency: Devices demand ultra-low latency for real-time collaboration
- Versatile connectivity: Communication to both static and mobile devices
- Multiple frequency bands: Versatile frequency support to ensure robust communication
- Energy efficiency: Performance and sustainability through energy-efficient design
- Interoperability and standardization: Compatibility and seamless integration with other devices

Other characteristics:
- Accurate positioning: Precision positioning for optimal operations
- Time synchronization: Accuracy to coordinate and data exchange
- 3D positioning: To enhance precision in use-case like cobots
- Local computation: Data analysis, filtering, and inference
- Security and privacy: Ensure confidentiality and unauthorized access
- Use-case specific: Features like safe axis range, detecting collisions, task assignment, etc.

Technology Enablers:
- Use of 6G spectrum for space sensing and communication capabilities.
- Integration with LiDAR, 3D imaging for mapping, obstacle avoidance.
- Sensing with precise perception and data collection.
- NLP, gesture recognition, and augmented reality for human-cobot seamless collaboration.
- Power-saving, secure communication, and effective energy management for reliability and safety.

Note: Technology enablers are use-case dependent.

Device class #3: High Reliability & Low Latency (HRLL) devices (2/2)

System/infrastructure Enablers
- Edge compute to complement onboard computation
- RIS as an enabler to improve reliability, availability and enhance coverage

Sustainability considerations
- Environmental: Optimizing power consumption and energy usage (minimize maintenance efforts and support sustainable and cost-effective operation).
- Social: Ensuring consistent and dependable connectivity, data transmission, and system operation to support critical industrial processes and applications.
- Economic: Enabling seamless integration and communication among heterogeneous Industrial IoT (IIoT) devices.

Key performance parameters
- Accurate positioning to 1 cm
- Low latency e.g., 1-50 ms for collaborating robots
- Coexistence with other networks, network scalability
- Multi-hop capability to improve network resilience and overcome obstacles or signal interference that may exist in complex industrial environments.
- Power management, standby mode, consumption (peak, idle, active) and monitoring

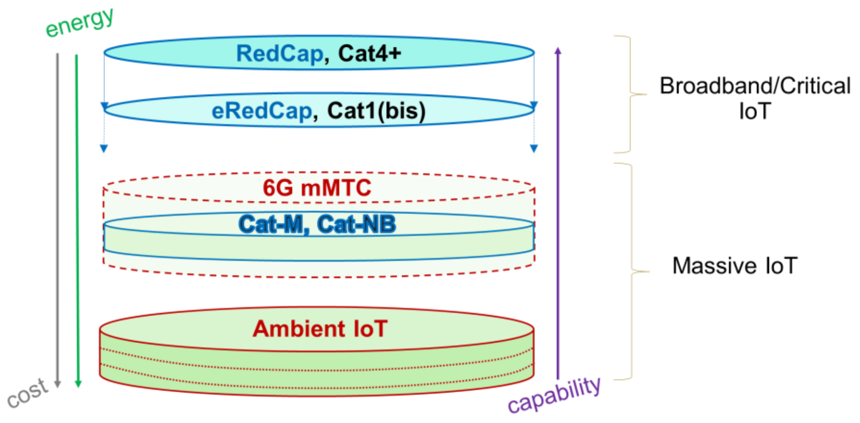
Link to use-cases
- Outdoor and indoor deployment (e.g., construction sites, agriculture, etc.)
- Warehouse inventory management, remote health, telesurgery, manufacturing sector, etc.
- Predictive maintenance, monitoring, etc.

Example devices
- Cobots (Telesurgery, robotic arms, exoskeletons, etc.)
- IIoT like asset tracking, wearables, smart sensors, etc.

Device class #4: Enhancements of mMTC (EmMTC) devices (1/2)

Enhancements of mMTC devices : devices for mMTC will continue to improve on device cost and energy conservation, enable slightly higher data rates while ensuring high coverage, add requirements on reliability or joint communication and sensing capability, may incorporate lightweight AI/ML techniques (e.g., AI-based channel estimation), etc., when compared to 4G/5G mMTC devices.

Key characteristics:
- Low device complexity and cost
  - E.g., up to ~1/3 of broadband/critical IoT device
- Small data volumes
  - Potentially infrequent and asymmetric (e.g., UL heavy)
- Enhanced coverage
  - Several km (>10) outdoors, deep underground
- Long lifetime
  - May rely solely on battery for several (10-15) years under extreme coverage
- Fixed to High Mobility
  - Up to 120 km/h, potentially also above



Cellular IoT (4G → 5G → 6G)

Other characteristics:
- Potentially small form factor
- Limited battery capacity/size
- Expectation of long duration wearability
- Large connection density
- Relaxed latency and availability
- Potentially high accuracy positioning/sensing
- Secure device and communication

Technology Enablers:
- Power saving techniques and design
  - sleep modes, low-power access, low-power wake-up
- Cost effective design and operation
  - HD-FDD, narrow channel BW, precoding for low # Tx/Rx paths
- Coverage enhancement techniques
  - low-energy coverage recovery, deep synchronization
- Coexistence with 6G air interface and core network
  - efficient DSS, legacy procedures support

Note: Technology enablers are use-case dependent.

Device class #4: Enhancements of mMTC (EmMTC) devices (2/2)

System/infrastructure Enablers
- Ubiquitous low-power wide-area network deployment
- Network capability to support concurrently large device connection density
- Cloud and edge computing platforms for device offloading

Sustainability considerations
- Environmental: Low energy consumption and demand throughout the entire device life-cycle, from manufacturing, to operation, to disposal; Low resource/energy usage impact per device to the network
- Social: Ubiquitous and on-demand coverage (digital inclusion); low-cost wearable and sensor services for, e.g., accessible and remote healthcare (digital inclusion, well-being); Low-cost, ubiquitous & private emergency services with high connection density (well-being, equity, security)
- Economic: Low-cost solutions deployed in mass scale; Low resource/energy usage impact per device to the network

Key performance parameters
- Data rate: from 10s kbps to few (<10) Mbps
- Coverage: up to 164 dB MCL @160 bps
- E2E latency: few (10-15) ms to few (≤10) sec
- Service availability: ≥99%
- Connection density: up to 1 device per m^2
- Energy consumption (modem): Dormant: ~1uA;
  Reachable state: few 10s uA; Idle: few mA; Active: few 100s mA

Example devices
- Smart devices
- Wearables
- Trackers
- Meters
- Sensors

- Smart Watch
- Patient Monitors
- Connected Audio
- PoS Terminals
- Alarm Panels
- Connected Healthcare
- Enterprise PDA
- Kids watch

- Fleet Tracker
- Activity Tracker
- Asset Tracker
- Gas/Water Meter
- Electric Meter
- mPERS
- Personal/Pet Tracker

- Smoke Detector
- Parking Control
- Pollution Monitor
- Lighting
- HVAC Control
- Agriculture Monitor
- Industrial Monitor

Link to use-cases
- Affordable and reliable connectivity for on-body monitoring and basic e-health services that can be delivered anywhere
- Massive connectivity density in challenging coverage environments for management and risk prevention of city infrastructure
- Connected large populations of sensors in machines/vehicles for energy and spectrum efficient production and manufacturing

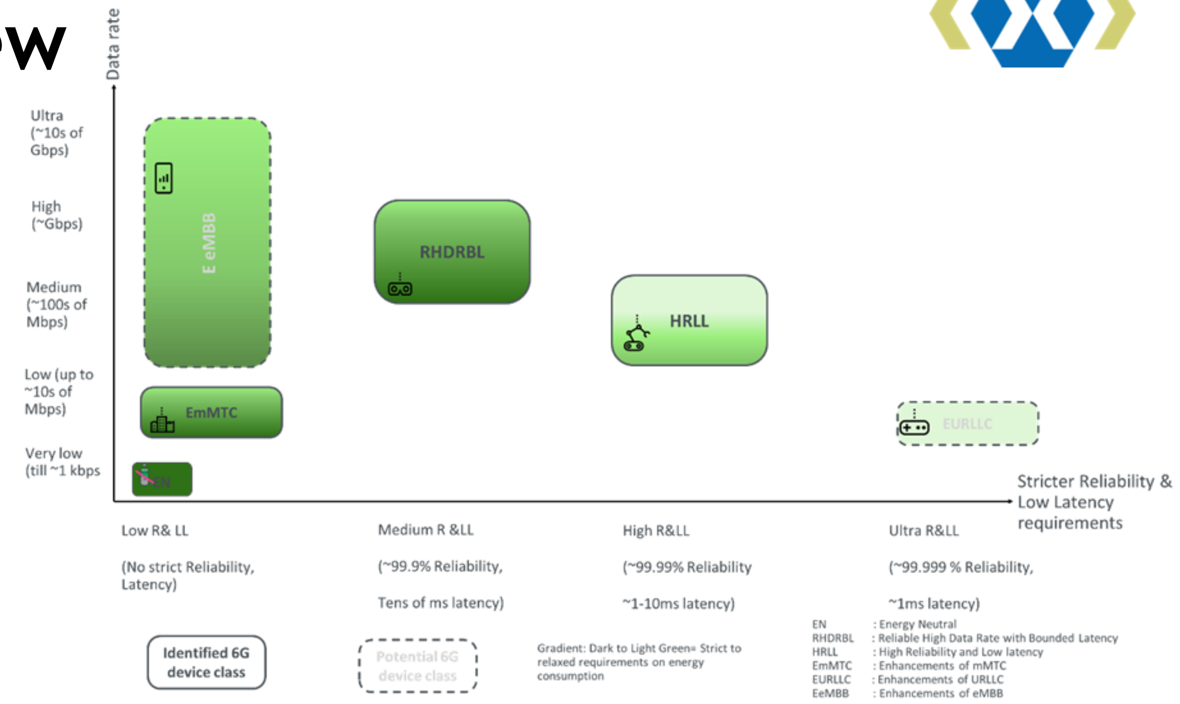
Chapter 5

Conclusions and Outlook

Conclusions and Outlook: Overview

Identified 6G device classes

- Three device classes, novel from 5G (eMBB, URLLC, mMTC)
  - Energy Neutral (EN)
  - Reliable High Data Rate with Bounded Latency (RHDRBL)
  - High reliability and low latency (HRLL)
- One device class, enhancement of existing 5G device type
  - Enhancements of mMTC (EmMTC)



Possibilities for future work

- From use-case trends and analyzing services to be supported
  - Enhancements of eMBB devices
  - Enhancements of URLLC devices
- Understand how sensing aspects influences the device classes and the role of companion devices (devices that mainly enables CaaS at extreme edge, advanced & secure compute for low capability devices)
- Hexa-X-II will update the use-cases and associated KPIs.
  - This implies that some of the above identified & possible device classes will be updated/refined in upcoming WP5 deliverables.

Conclusion and Outlook: Deltas w.r.t 5G

Legend	5G Device classes	6G Device classes	Comments
Novel	• eMBB • URLLC • mMTC	• Reliable High Data Rate with Bounded Latency (RHDRBL) • High reliability and low latency (HRLL) • Energy Neutral (EN)	**RHDRBL**: high data rates, with bounded latency to reliably serve for, e.g., immersive experience use-cases **HRLL**: higher data rates than URLLC but less stringent reliability requirements targeting devices that have more safety requirements and autonomous operation including with collaboration with humans (device class will be further analysed along with enhancements of URLLC together with developments in use-cases) **EN**: enables energy efficient massively deployable devices
Enhancements from 5G	-	• Enhancements of mMTC (EmMTC) • Enhancements of eMBB (EeMBB) • Enhancements of URLLC (EURLLC)	**EmMTC**: improved cost/energy, higher data rates while ensuring high coverage, possibly requirements on reliability, integrated sensing capability, lightweight AI/ML techniques **EeMBB**: higher data rates (perhaps also lower data rates) without latency requirements, new spectrum bands **EURLLC**: new spectrum (for e.g., in cmWave), physical layer enhancements, optimization enabled by ML/AI
Potentially novel from 5G	-	• Companion devices	To mainly augment lower capable devices with secure, advanced compute and connect them via flexible topology. Companion devices may have only limited possibilities for deployments.

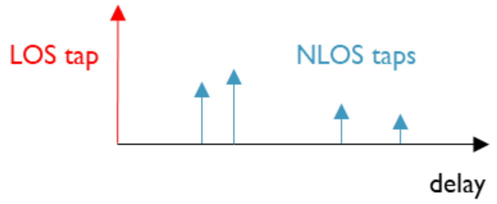
Appendixes

Details on Selected topics

Appendixes

Appendix A: Sub-THz transceiver design

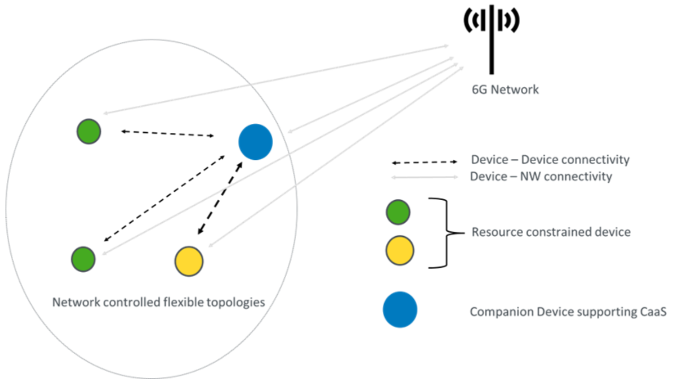
- Essential technology enabler for very high data rates
- Outlines design methodology
- Covers scenario parameters
  - Application requirements
    - Range, throughput, #users, …
  - Band of operation and regulations
  - Propagation channel: Line Of Sight (LOS) or Non-Line Of Sight (NLOS)
    - Delay domain statistics



  - Transceiver architecture constraints

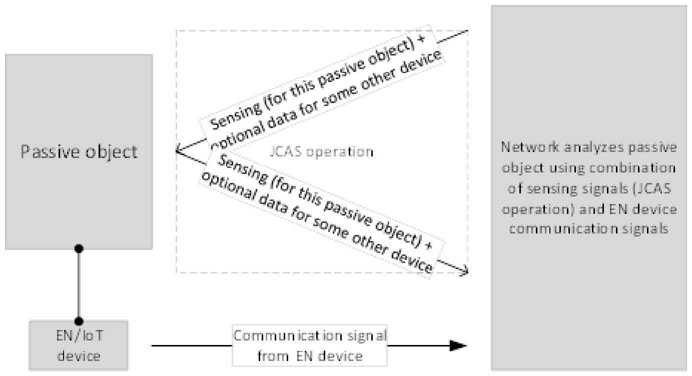
Appendix B: Companion Devices

- Enhance the capabilities of another less capable <u>device</u> guaranteeing security/privacy and possibly energy savings.
- A potential new device or can be an add-on feature of existing device. It needs further analysis, also considering use-case updates and KPIs. Potential update in future deliverables.



Appendix C: Example of novel device enabling a 6G capability

- Describes how EN can enable JCAS, an expected 6G capability.
- An example scenario is depicted wherein EN devices facilitates, for instance, to remove clutter or monitor known or partially known passive objects



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