HEXA-X-II

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

Deliverable D5.2
Characteristics and classification of 6G device classes

Co-funded by the European Union

6GSNS

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Abstract

This report presents, based on Hexa-X-II use-cases defined so far, the characterization criteria, identified 6G device classes along with their characteristics and their technological enablers and provides an outlook for future considerations.

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[1] SEN = Sensitive, only members of the consortium (including the Commission Services). Limited under the conditions of the Grant Agreement

PU = Public

Keywords

6G, Future devices, Device Classes, Device characteristics, Technology enablers, Sustainability considerations

Disclaimer

Executive Summary

This report –” Characteristics and classification of 6G Device Classes” is the second deliverable from Work Package 5 (WP5). It analyzes the use-cases 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, and defines the characterization criteria to identify 6G device classes and technological enablers to address WPO5.1.

From a set of use-cases, this deliverable builds an understanding of key devices that realize a use-case while noting the deployment characteristics and its influence on the device operation. This helps to build a broad idea of the devices and how they will be integrated in a 6G System.

This deliverable then defines a set of characterization criteria which serves as a basis to extract distinct characteristics that distinguish individual device classes from each other and other characteristics that these devices may share but to varying degrees. Furthermore, from the Hexa-X-II D1.1 deliverable, set of guidelines on the sustainable design is identified to serve as recommendations to these device classes.

Four device classes are identified – *energy neutral* devices, *reliable high data rate with bounded latency devices*, *highly reliable and low latency devices*, and *enhancements of massive Machine Type Communication (mMTC) devices*. Energy neutrality will gain more prominence as the number of the devices continue to rapidly increase and with energy neutral device class, devices that rely only energy harvesting are addressed. They are recommended to generate zero e-waste, taking advantage of environment friendly material and manufacturing. Zero energy devices fall into this class. The Reliable high data rate with bounded latency device class caters to enabling immersive experiences and beyond what is possible in 5G. This device class covers the eXtended Reality (XR) devices and identifies the trade-off between availability and Quality of Experience (QoE). A third device class would be one with high reliability yet have increased data rate and less stringent latency than what is supported in 5G URLLC. These devices will have functional safety as a prominent non-communication criterion and cover the autonomous operating devices. Cobots, AGVs fall into this class. Lower data rates, yet with more reliability and availability than energy neutral devices lead to the fourth device class, which is seen as an enhancement of mMTC devices in 5G. They are battery operated, will enable low power and wide area IoT.

From the current outlook, there could be additional devices that are evolutions of *enhanced Mobile BroadBand (eMBB)* and *Ultra-Reliable and Low-Latency Communication (URLLC) devices*. These devices emphasize the support for higher data rates & ultra-reliability respectively, potentially on new spectrum in centimetric range, sub-THz range and identifying the technology challenges they entail, and perhaps bringing in Machine Learning based techniques to find enhancements. Furthermore, there could be companion devices that support less (compute) capable devices by providing a secure, privacy aware compute connecting serving devices by flexible topologies.

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Acronyms and abbreviations

Term	**Description**
ADC	Analog-to-Digital Converter
AGV	Autonomous Guided Vehicle
AI	Artificial Intelligence
AR	Augmented Reality
CaaS	Compute-as-a-Service

CE	Coverage Enhancement
CPU	Central Processing Unit
CSI	Channel State Information
DAC	Digital to Analog Converter
DL	Downlink
DoF	Degrees of Freedom
DRX	Discontinuous Reception
D2D	Device to Device
eGPRS	enhanced General Packet Radio Services
EH	Energy Harvesting
EIRP	Equivalent Isotropic Radiated Power
eMBB	Enhanced Mobile BroadBand
EeMBB	Enhancements of Enhanced Mobile BroadBand
EmMTC	Enhancements of Massive Machine-Type Communication
EURLLC	Enhancements of Ultra-Reliable and Low Latency Communications
EMC	Electromagnetic Compatibility
EMG	ElectroMyoGraphy
EN	Energy Neutral
E2E	End-to-End
FDD	Frequency Division Duplexing
FOV	Field of View
FR	Frequency Range
GPU	Graphic Processing Unit
HD-FDD	Half-Duplex Frequency Division Duplexing
HMD	Head Mounted Display
HRLL	High Reliability and Low Latency
IIoT	Industrial Internet of Things
IoT	Internet of Things
JCAS	Joint Communication and Sensing
KPI	Key Performance Indicator
LEO	Low-Earth Orbit

LOS	Line Of Sight
LPWAN	Low Power Wide Area Network
LTE	Long Term Evolution
MCL	Maximum Coupling Loss
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
mMTC	Massive Machine-Type Communication
mmW	Millimeter Wave
MQTT	Message Queuing Telemetry Transport
MTC	Machine type Communication
NB-IoT	NarrowBand IoT
NLOS	Non Line Of Sight
NLP	Natural Language Processing
NoC	Network on Chip
NR	New Radio
NTN	Non-Terrestrial Network
OFDM	Orthogonal Frequency-Division Multiplexing
OS	Operating System
PB	Power Beacon
PDB	Packet Delay Budget
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RedCap	Reduced Capability
RF	Radio Frequency
RFID	Radio-Frequency Identification
RHDRBL	Reliable High Data Rate with Bounded Latency
RIS	Reconfigurable Intelligent Surface
RRC	Radio Resource Control

RTT	Roundtrip Time
Rx	Reception
SINR	Signal-to-Interference-plus-Noise Ratio
SoC	System on Chip
TEE	Trusted Execution Environment
TLS	Transport Layer Security
TN	Terrestrial Network
ToA	Time-of-Arrival
TSN	Time-Sensitive Network
Tx	Transmission
UAV	Unmanned Ariel Vehicle
UE	User Equipment
UL	Uplink
URLLC	Ultra-Reliable and Low Latency Communications
V2X	Vehicle-to-everything
VR	Virtual Reality
WET	Wireless Energy Transfer
XR	eXtended Reality
ZE	Zero Energy

1 Introduction

While the Hexa-X project successfully framed a 6G wireless network vision, the Hexa-X-II project will continue to build on the core of enablers and architecture that was explored in Hexa-X [HEX223-D210]. The components will be systemized into a platform that offers 6G services in Hexa-X-II. Also, in Hexa-X-II this platform will be validated considering key requirements from the perspective of societal values and ecosystems. This is the second deliverable from Work Package 5 (“Future devices and flexible infrastructure”) in Hexa-X-II and the first publicly available one.

1.1 Scope and objective

The main contribution of this deliverable is to classify the new device types and associated radio requirements, along with technological enablers, beyond current 5G devices to be addressed specifically in 6G. Thus, it addresses the 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”). This WPO5.1 in turn contributes to Hexa-X-II Objective 3 (“Develop and describe radio access solutions for communication considering the requirements on 6G services”).

A subset of envisioned use cases for 6G networks cannot be enabled by relying solely on existing device classes tied to 5G services (i.e., eMBB, URLLC, mMTC). An exhaustive set of device characterization criteria is subsequently defined to identify the device requirements needed to enable these novel 6G use cases (cf., Chapter 3). The criteria go beyond the three axes defined for 5G (i.e., scale, latency, and capacity) and include energy, lifetime, mobility, communication capabilities, computing & AI capabilities, localization & sensing, and security concerns. This in turn allows defining an additional set of device types that are needed to cover all envisioned 6G use cases and applications (cf., Chapter 4).

Within the context of Hexa-X-II in general, and this deliverable in particular, we define 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 1-1, the considered device consists of RF transceiver circuitry, a System-on-Chip (including a CPU, memory, and peripherals), and the necessary firmware and software.

In this deliverable, we additionally consider a set of infrastructure-enablers that aid the network and devices to achieve the use case requirements. These enablers are not considered to be devices per se, as they do not generate or consume application data. Examples of such enablers include Reconfigurable Intelligent Surfaces (RIS), repeaters, or relays.

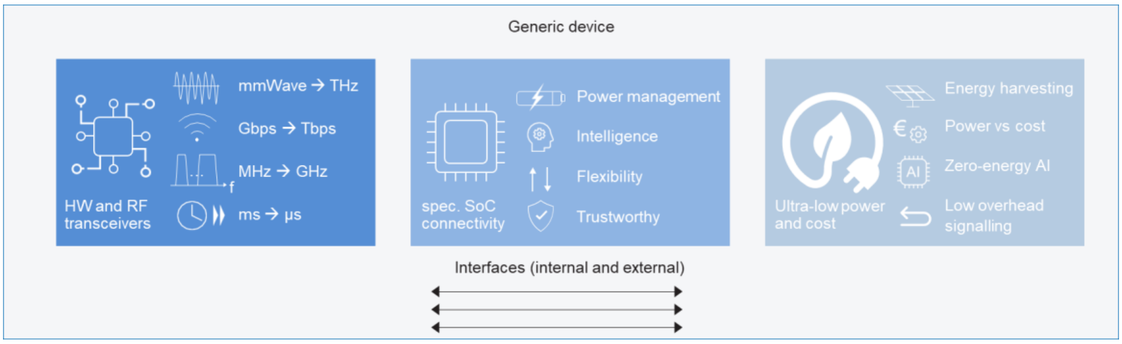

Figure 1-1: Hexa-X-II generic future device concept

1.2 Methodology

Figure 1-2 depicts the methodology followed to identify the device classes and the role characterization criteria play. The Hexa-X-II use-cases as described in [HEX223-D110] complemented with similar ones described in Hexa-X project such as [HEX21-D12], [HEX22-D13] and [HEX23-D14] are analyzed to extract the key device types and understand the deployment scenarios in which they operate along with the KPIs. This is 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.

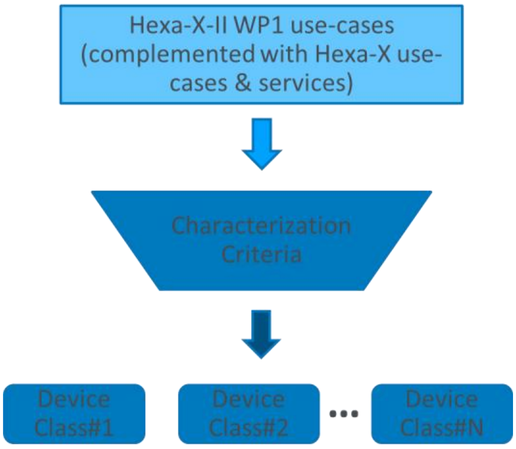

Figure 1-2: Methodology to identify 6G device classes in Hexa-X-II

1.3 Structure of the document.

This document is structured in the following way: Chapter 2 introduces the motivating use-cases and services that are analyzed to get an understanding of the diverse set of devices that are enabling them and scenarios in which they are deployed. Chapter 3 provides a set of characterization criteria that is utilized to identify key aspects of the different devices to arrive at distinct device classes. This chapter also brings an understanding on sustainability guidelines that are described in [HEX223-D110] to set a basis for developing an initial set of sustainability considerations as seen from different device classes. Chapter 4 presents the different device classes. The document concludes with conclusions and outlook in Chapter 5, where we indicate the possible influences on device classes. Appendix A indicates the design aspects related to the sub-THz RF transceiver design. Appendix B outlines a possible novel companion device whose roles and features will be further defined in the future deliverables as use-cases and KPIs will be updated. Appendix C provides a deployment scenario wherein devices belonging to a novel device class can enable a 6G capability.

2 Motivating use-cases and services

The following Figure 2-1 depicts an overview of initial use-cases from [HEX223-D11]. In this section, we select a sub-set of use-cases that give a good representation from a wide set of application scenarios and verticals and is based on [HEX223-D11] and complemented by detailed descriptions from [HEX21-D12] and [HEX22-D13]. Similarly, a sub-set of services from [HEX21-D12] and [HEX22-D13] are analysed, which have more prominent influence on devices. In relevant topics, some of the use-cases are complemented with inputs form other organizations such as 3GPP. In the upcoming deliverables from Hexa-X-II project, it is expected that more work will be done on use-cases and the KPIs associated with them along with identifying the deltas with respect to 5G use-cases.

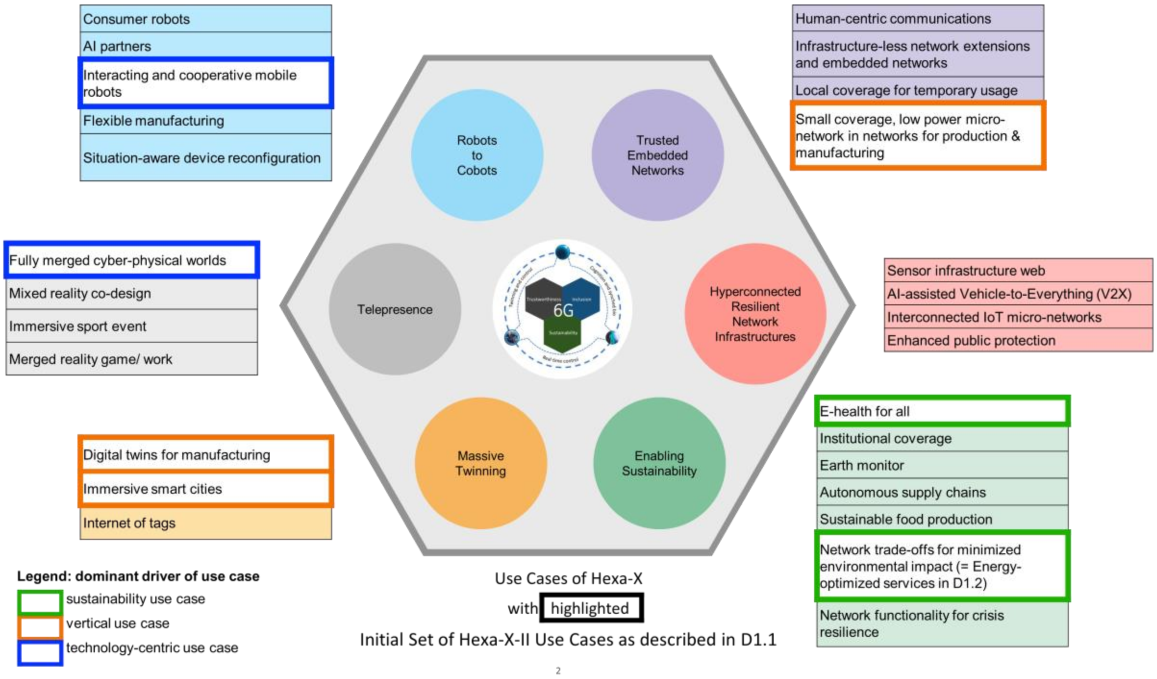

Figure 2-1: Initial set of use-cases as described in Hexa-X-II [HEX223-D11]

It is good to note that from the initial set of Hexa-X-II use-cases, when analyzing use-cases in this deliverable, *Digital Twins for manufacturing* and *Network trade-offs for minimized environmental impact* are not considered but *Earth monitor* and *Autonomous supply chain* are analyzed instead, to have a representative from all device categories.

The set of devices and deployment scenarios under which they are operate, in each of the above use-cases, are detailed under following corresponding sub-sections. The objective is to identify the characteristics that are common and those that are distinct across a set of devices that realise a use-case.

2.1 Use-cases

2.1.1 Autonomous supply chains

To track and manage supply chains globally from production, shipping, distribution, usage and recycling, there is a need for an efficient mechanism which can monitor, assist, and fasten different supply chain phases. This can increase resource efficiency, reduce material and energy consumption, save time and wastage with timely updates and delivery. It can also raise the awareness of information related to origin of products and commodities and assist in recycling or environmentally friendly disposal of products, etc. The use cases can also be differentiated based on targeted products or services, for e.g., in the areas of automated supply distribution, fresh food supply chain, end-to-end logistics, non-public network for logistics, logistic handling at airport terminal / shipping port, etc. [22.840].

The 6G-connected network should envisage supporting devices, such as zero energy (ZE) devices, IoT sensors, etc. which can be fitted with goods, transportation infrastructure to simplify tracking, customs, safety checks, and bookkeeping, allowing it to be done without manual interference. The use case can be combined with flexible or smart manufacturing enabling supply chain management much more dynamic and flexible to cater to the much more varied needs for resources.

The devices should have good indoor and outdoor coverage (use sub-6 GHz). The devices build on the work done with Narrowband Internet of Things (IoT), New Radio (NR) Reduced Capability (RedCap), Ambient IoT or 6G-alike device capabilities with Terrestrial Networks (TNs) and Non-Terrestrial Networks (NTNs) and integration of Artificial Intelligence (AI)/Machine Learning (ML) (at the network side). Due to the utilization of different Radio Access Technologies (RATs) and different generation networks, 6G-connected devices must support inter-operability.

2.1.2 E-health for all

This use case, detailed in [HEX21-D12] stresses on importance of remote and accessible healthcare by utilizing a plurality of technologies, topologies, and connectivity features. These network elements and features should support communication and device integration handling pertaining to communication related to:

- eMBB: video calls, or remote medicine consultation, or connection to experts, doctors or nurses; basic E-health services,
- NTN and satellite communication: connections to patients in far flung areas or connection between remote health/medicine unit and labs in developed areas; drone communication with provisioning of dropping medicines and emergency kits,
- Augmented Reality (AR) or eXtended Reality (XR) communication: remote diagnosis or virtual diagnosis,
- On- and in-body monitoring: Communication providing to sensors – lightweight, or low power or zero-energy bio-devices/sensors/tags/implants/stickers which are monitoring conditions or supporting the function of human organs,
- ZE communication: Medicinal tools equipped with location finder tags; medicines and vials equipped with sensors monitoring their temperatures or environmental conditions surrounding it; on- and in-body ZE sensors. Some of the use cases are also being targeted in [22.840], e.g., medical instruments inventory management or positioning, or finding remote lost item, etc.
- Haptic and neuro-based interfaces
- AI agent support: Providing first-line support complimented by local analysis of samples.

The tight integration between different topologies, and network elements are needed for cost-efficient deployments and operations, even to underserved regions where the coverage becomes the major challenge.

Regarding deployment characteristics, both indoor and outdoor deployment are required but with a more focus on indoor given major use cases with static housed indoor, and for outdoor scenarios, there could be few scenarios with the delivery of medicines and kits. For spectrum, both high and low bands are extremely important, for instance lower bands, such as sub-6 GHz are useful for coverage and higher bands such as in millimeter Wave (mmW), on the other hand, are useful for capacity, e.g., AR or XR based traffic originating from remote diagnosis applications.

2.1.3 Earth monitoring

Earth monitoring uses a global distribution of sensors to monitor environmental indicators, signs of anomalies and issuing alerts, which also urges humanity to act with sustainability in mind, providing opportunities to think about what can be done to realize a sustainable future and take concrete action. Earth monitoring can include plurality of use cases and events, such as monitoring of climate and natural disasters (e.g., landslides, flooding, forest fires), illegal logging, poaching activities in order to monitor biodiversity loss and endangerment of protected species, public infrastructure (bridges, dams), etc. It can also enable smart agriculture by control the facilities such as irrigation system and temperature control system as per the environmental conditions.

The earth monitoring system mainly targets to cover outdoor environment for both static and mobile scenarios (e.g., tags on endangered species, unmanned aerial vehicles (UAV) following species or monitoring the area), with devices that are bio-friendly energy-harvesting sensors that can easily be deployed anywhere with cost-effective connectivity via, for example, NTN, long-range TN, or local mesh networks. In addition, IoT device, other low capability device, such as RedCap, and edge AI with ultra-low power are also considered to be important device capabilities to support earth monitoring network.

The sub-6GHz spectrum is expected to be used as primary frequency range for earth monitoring use case to provide a wide area coverage for the earth monitoring system while mm-wave and sub-THz frequency can be used for sensing purposes (e.g., RF sensing instead of camera in environment with poor visibility and mmWave radar for weather detection) and also for services that requires high data throughput (e.g., eMMB type services: video feed surveillance on poachers or data aggressive activities/events) or download large sensing data collected by a larger number of sensors from satellite.

Even though NTN network has been supported in 5G era, enhancement to both TN and NTN network with existing or new RAT are needed to allow also ultra-low power or ZE and (near) zero-cost biodegradable devices effectively communicate with them as described in [HEX21-D12]. Communication reliability is extremely important. In addition, enhanced network coverage, e.g., NTN network, TN-NTN interworking is needed to ensure the sensing network can be deployed anywhere. Finally, the RF sensing accuracy and utilization of the AI technologies to improve both sensing and communications are important aspects to be considered.

2.1.4 Immersive smart city

This use-case, detailed in [HEX22-D13] outlines an urban/suburban mixed indoor/outdoor scenario, where gathering data to create an accurate and real-time digital representation of a city; using insights generated from them and means that influence the physical world to manage many application areas (e.g., city infrastructure, air quality, healthcare aspects). Thus, the deployment characteristics [HEX22-D13] would compose of the very high number and possibly extremely high density ($10^7/km^2$) of devices, wherein quite some of the devices will have significant interactions with edge/cloud. In addition to capacity and densification challenges, there will challenges to maintain data flow integrity (e.g., radio propagation in underground roads), coverage, etc. These challenges must be addressed while meeting the KPIs [HEX22-D13] and the use-case will be enabled by a diverse set of devices such as ZE sensors, IoT devices etc.

2.1.5 Fully merged cyber-physical worlds

This use-case, detailed in [HEX22-D13], illustrates how 6G will support a mixed reality (MR) scenario, where the user can access both physical and virtual worlds with a seamless experience. It outlines an urban mixed indoor/outdoor environment such as street, park and/or mall, subway environments, where immersive XR devices can help the user combine both physical and cyber worlds. Thus, the deployment density and user mobility from network side can be seen like existing mobile phone density and mobility characteristics. More than one device can be connected directly to the network or locally connected to one device per user. Typically, physically present and telepresence consumers are equipped with AR glasses, wearables, and optionally smartphone/connectivity puck [HEX22-D13]. The frequency bands that can be supported for this use case include FR1(sub-6 GHz), FR2 (mmWave), potentially in upcoming bands in centimetric range/FR3 as well as sub-THz. The main enabling device that needs to be defined for this use case is the extended reality (immersive XR device type). It can operate with other devices such as IoT devices as well as smartphone/connectivity puck. As mentioned in [HEX22-D13], 6G must provide high reliability [99.9%], high data rate [DL 1 Gbps, UL 0.1 Gbps] and low latency [< 20 ms] to enable this use case. Also, 6G infrastructure should support multiple spectrum options to satisfy scalability and capacity (using sub-6 GHz), high data rate (using mmWave and sub-THz) or satisfy trade-off between both (using upcoming bands in the centimetric/FR3 spectrum).

2.1.6 Interactive and cooperating mobile robots

This use case illustrates how 6G will enable robotic systems to collaborate with each other and/or with humans in a reliable, autonomous way to achieve their common goal [HEX21-D12]. Such collaborative robot swarms can be deployed both outdoor (e.g., construction sites, agricultural plantations, etc.) as well as indoor (e.g., consumer homes, warehouses, production/manufacturing environments, etc.) [HEX22-D13]. As described in [HEX22-D13], on-premises 6G infrastructure must provide low latency (0.5 – 25 ms) communication to static and mobile (<10 m/s) automated guided vehicles (AGVs), UAVs and human operators to allow for reliable and safe interaction. To overcome environmental constraints such as Line-of-Sight (LoS) blockages, multiple frequency bands must be supported, i.e., sub-6 GHz bands for campus-wide coverage and higher frequency bands for local D2D communication. As safety is a crucial requirement, especially when interacting with humans, robots must be aware of their own position and the position of their peers. Therefore, accurate positioning (1 – 5 cm) must be supported at a 10 to 10000 Hz refresh rate. When involving UAVs, e.g., for warehouse inventory management, these challenges become increasingly difficult as 3D positioning is required.

2.1.7 Small coverage, low power micro-network in networks

This use case, with the full title “Small coverage, low power micro-network in networks for production & manufacturing” detailed in [HEX21-D12] and [HEX22-D13], relates to the envisioned 6G use case family of trusted embedded networks where high-level trustworthy communication capabilities of very sensitive information are required for sub-networks, or networks of networks, tightly integrated in wide-area networks. It considers the application where a machine manufacturer wants to mutually connect a large population of sensors in the machine using non-Industrial, Scientific, or Medical spectrum for reliability reasons. As described in [HEX21-D12], this can be seen as a shared spectrum access concept with infrastructure-less networks of very limited coverage as an underlay network under full control of the incumbent, involving large machine population interconnected via very low-power devices (resilient IoT sensor devices), potentially with one of the sensors getting the authorization out of the public or non-public network of which the spectrum is used (Trustworthy/Intelligent aggregator sensor node or smart IoT gateway device).

Regarding deployment characteristics, the typical environment will include rural areas as well as indoor case (e.g., production site) [HEX22-D13]. Very low-power devices will be needed to mutually connect sensors mounted in manufacturer’s machine or vehicle, with possibly high density of tens to some thousands of sensors (few sensors per cubic meter for manufacturing case). These sensors can be static (e.g., environment sensors) or mobile (when e.g., mounted to a possibly low mobility vehicle). Standard licenced sub-6 GHz frequency bands (shared with the infrastructure) can be assumed for low power consumption, but higher frequency bands might be used as well.

The main expected technical challenges originating from environmental or other constraints include electromagnetic compatibility (EMC) requirements (e.g., for sensor-to-sensor connectivity with proximity), small form factor and low-cost, and safety of operation requirements. Capabilities of data security (for protecting the processed proprietary information and guaranteeing the availability of the connectivity, independent of the infrastructure network), interference mitigation (due to dense deployment and flexibly shared spectrum), and localization in several cases, will be of paramount importance.

2.2 Services

2.2.1 Compute as a Service

Compute-as-a-Service (CaaS), which is a service described in [HEX21-D12] and [HEX22-D13], is also analyzed as some of the low capability devices need to rely on this service to augment their compute capabilities. CaaS is more of a use-case enabling service and could enable devices, especially resource-constrained ones, to delegate resource intensive processing tasks. For example, CaaS may be used for storing and processing of sensory data collected from special equipment such as glasses, gloves vests etc in an industrial setting. Another example could be in multi-player gaming where complex games may be processed on computational resources in the network.

Thus, typical deployment of CaaS will be for devices with limited compute capability that could be operating in both indoor and outdoor environment. Such devices could be sensors that are static or wearables that would have mobility. These devices could be operating on FR1(sub-6 GHz), FR2 (mmWave) and potentially future ones in centimetric range as well as sub-THz as dependent on the application/use-case.

To deploy CaaS, some of the notable technical challenges that should be addressed are discovery of suitable CaaS providing entity and therein ascertaining available compute resources, trustworthiness, energy footprint etc., decision on when and where to offload (based on current/predicted resource availability and performance of the service providing entity) and simple, generic interfaces that are abstracted from underlying heterogenous hardware (e.g., Central Processing Unit (CPU), hardware accelerators etc.) and software (e.g., Operating System (OS)) as much as possible to request/execute the service. Though depending on exact application or usage scenario it can be anticipated that devices needed to support high availability, high reliability, low latency in addition to overall improved energy efficiency while ensuring high security and user data privacy. For example, AR glasses offloading resource intensive tasks to another capable trusted node would require reliable low latency communication to the service providing node, which can ensure user data privacy.

2.2.2 Situation aware device reconfiguration

Situation aware device configuration, as described in [HEX22-D13], represents a transformative service poised to enhance the capabilities of interconnected devices. This service empowers devices with the agility to dynamically alter their device types and configurations to align seamlessly with evolving service requirements. Device endowed with this service gain the remarkable ability to transition between different device types, harnessing diverse processing capacities and functionalities based on the precise demands of the active service. This dynamic metamorphosis ensures that the device is optimally configured to deliver peak performance for the task at hand. This service can not only respond to existing requirements but also predict future demands. These predictive insights enable devices to anticipate the need for a change in device type and timing, ensuring a proactive response that guarantees uninterrupted service excellence. The challenge for 6G systems lies in the extremity of performance requirements for new applications, for the addressment of which current 5G solutions may need to be enhanced. Flexible device type change may evolve today’s network slicing concept in 5G to the one of device slicing.

In one instance of the usage scenario of situation aware device configuration service, a familiar consumer device like a smartphone seamlessly shifts roles upon entering Vehicle-to-everything (V2X) communication zones, transitioning from its usual voice/data function to become a conduit for safety-related communication, ensuring warnings for vulnerable road users and facilitating vehicle-to-network services. In another scenario, an industrial robot adeptly toggles between critical tasks like high-precision welding demanding minimal latency and exceptional localization accuracy, and less critical tasks involving longer-range movement with more moderate precision and latency requirements. These examples showcase the dynamic adaptability and performance optimization enabled by this innovative service, poised to redefine device interactions.

2.3 Summary of motivating use-cases and services analysis

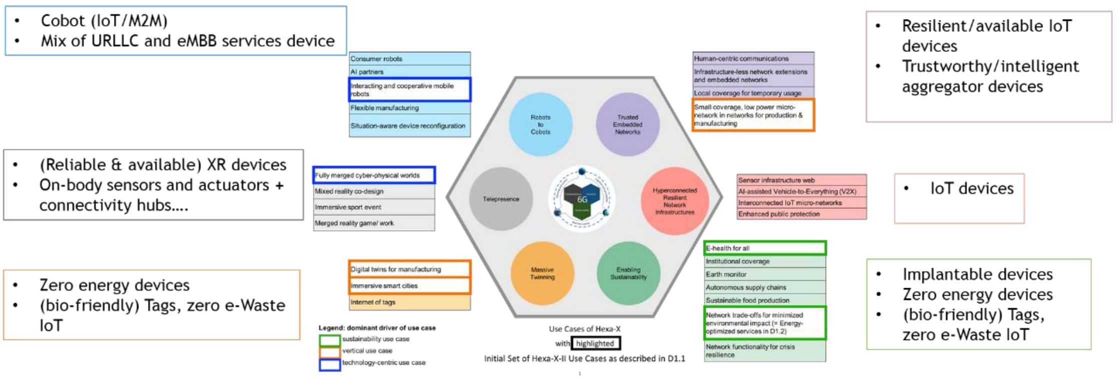

Figure 2-2: Use-cases and some example devices realizing them.

One key takeaway after analysis of various use-case and services is that one use case may need multiple types of devices to realize it. The other angle is also relevant – a device could serve multiple use cases. For example, energy efficient sensors that rely on energy harvesting as an energy source could play a contributing role in Earth monitoring as well as in Immersive smart cities. Another notable takeaway is that one device type could have varying implementations depending on the use-case it serves. For example, an IoT device could have integrated circuit design signoffs done for different temperature range for consumer use-case deployments than one that should be deployed in an industrial scenario. Another aspect could be the placement of antenna: in some industrial robots it might be placed close to the device's radio front end components while in some other devices it might be placed remotely to enhance reception. Furthermore, if a device must operate in a low coverage or have high mobility then it may be designed with only supporting low frequency spectrum. Thus, a device design could be adapted to the use-case it is serving and its deployment scenarios. Furthermore, a single device can have multiple capabilities. As seen from Section 2.2.2, a device may operate in one operating mode where it is catering to one service and then in another operating mode where it caters to another service. Such devices could be dynamically re-configured as well, but in essence it belongs to one device class/type as all features need to be implemented. In one operating mode some features (e.g., sensing) are more used or even enhanced than other features (e.g. communication). Along the similar lines, a sensing and communication device utilizing the same radio spectrum could be seen as a multi-mode device and not as a new class of device.

3 Characterization criteria and sustainability guidelines

This chapter outlines the characterization criteria that sets the basis to understand if the different devices in the 6G timeframe fall into a one device class or another. Furthermore, the sustainability guidelines from [HEX223-D11] are summarized in chapter 3.2 to enable identifying the sustainability considerations for each identified device class.

3.1 Characterization criteria

There are numerous characteristics concerning a device, such as its energy consumption, operating spectrum, authentication etc. Table 3-1 below contains the characteristics that form the characterization criteria, along with some description that also provides some granularity for each of these characteristics. 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.

Table 3-1: Characterization criteria

Group	Characteristic	Description	Comments
Energy	Energy source	Energy source for the device: {generated on-device (for e.g., energy harvesting based), generated remotely (e.g., power grid charging a local on-device battery)}	
	Energy storage	Identify storage type {Battery, super capacitor, None}. Indicate storage material with environmentally material or not	Identify if it enables zero e-Waste.
	Energy consumption during (1) operation (2) idle/sleep	Distinguish between active operation and sleep power.	Difficult to have exact numbers as they are use-case and implementation dependent indicate a range (in mW)
Lifetime	Device lifetime	Indicate if the device has a lifetime that is within a cellular network generation (Nth G), or its deployment can span multiple network generations (for e.g., Nth G, (N+1)th G	This is dependent on the usage scenario (e.g., discardable smart tags, infra sensor). Device design/manufacturing aspects such as battery lifetime (if irreplaceable), material lifetime, etc. could also influence.
Mobility	Device mobility	Fixed device or Mobile {low (human powered), medium/ (car, train <200 kmph), high (airplane >200 kmph}	Impact on radio propagation, fault fixing, life cycle management. Indicate typical speeds based on the deployment scenario.

Communication	Authentication	Distinguish between light weight/device energy aware authentication or typical authentication.	All devices shall be uniquely identifiable on the network.
	Synchronization	Distinguish if the device supports Timing as a Service	
	Time aware system component	Distinguish if the device has time aware system components (e.g., Device Side-TSN Translator in a TSN)	Identify if the network is a part of a bigger time-aware system. E.g., Time Sensitive Network based IoT system.
	Spectrum	Distinguish between new (cmW, sub-THz) and existing spectrum (FR1 and FR2) & licensed and unlicensed	Mainly identify impact on the front-end RF and antenna components.
	Traffic flow	Distinguish between {sporadic/aperiodic, energy source dependent traffic flows, Quasi periodic, periodic, ...}	Identify the impact on the latency and power consumption
	Data rate	Distinguish between the typical data rates that are supported.	
	Latency	Distinguish between the bounds on the latency- {none, time critical/bound, URLLC, …}	
	Reliability	Distinguish between levels of reliability at a coarse level: {none, exists, stringent}	Percentage of the amount of sent packets delivered within QoS constraints.
	Availability	Availability requirements to be supported.	
	NTN support	Yes/No	Indicates if the device supports Non-Terrestrial Network (NTN) in addition to TN. And if supported, indicate the services supported: is it for only emergency call, or also data call etc.
AI & computation	Computation capability	Distinguish between {Low, medium, high, AI-enabled, offloading dependent,}	Identify computational capability and dependence on other entities. *Low* computation capabilities indicate simple circuits, micro-controller-based

			designs etc., while *Medium* indicates CPUs, low end GPUs etc. *High* end computation capabilities would have additional dedicated HW accelerators, high end GPUs, CPUs etc. AI-enabled is an additional qualifier for identifying devices running ML kernels, while offloading dependent indicates devices that need another more capable remote compute to perform its functionalities.
Localization & sensing	Location accuracy	Distinguish if the device type has requirements on location accuracy and if yes, in horizontal & vertical position accuracy (in m)	
	Orientation accuracy	Distinguish if the device type has requirements on orientation accuracy and if yes, for roll, pitch, yaw (in degrees)	
	Localization/sensing latency	Distinguish if the device type has latency requirements w.r.t. localization/sensing service latency and if yes, indicate granularity of requirements {low, medium, high} latency.	
Security	Security capability	Security (e.g., encryption, data integrity) features supported on device. Distinguish between {*none/minimal*, medium *secure*, *highly secure*, *specialized*}	This parameter is about the security features supported on the device and indicates the potential vulnerabilities/risks. *None/minimal* level is for devices such as low-cost IoT sensors or older devices that have minimal/no built-in security features such encryption, secure boot, no updates etc. *Medium secure* level is for devices that have some amount of security features such as single level depth of defense, Trusted Execution Environment (TEE) etc. but

			have less features than highly secure devices. *Highly secure* level for devices that assume zero trust and support advanced features such as hardware root of trust, multiple levels of depth of defense, dedicated secure vaults etc. [HLN20]. Furthermore, the highly secure devices could undergo rigorous testing etc. as these devices could be part of the critical infrastructures and support specialized features such as permanently de-activate a device that is de-commissioned from the 6G system, dedicated processing solutions could be cryptographic acceleration sub-systems, secure Network on Chip (NoC)/interconnects.

3.2 Sustainability guidelines

As part of the effort to creating a sustainable future, the device classes also indicate some of the important sustainability considerations to be taken into account during each device class design.

The sustainability considerations are based on the sustainability guidelines provided in [HEX223-D11]. These guidelines are organized under environmental sustainability, social sustainability and economic sustainability and are detailed in the following sub-sections.

3.2.1 Environmental sustainability

To create a more sustainable and resilient communication system, 6G technology design need to incorporate environmental sustainability considerations in the planning, architecture and operation of the network, including:

- Holistic footprint approach – 6G network will have different footprints and thereby different environmental impacts. A holistic and comprehensive approach to different footprints, taking into account all the trade-off between different sustainability factors is necessary.
- Alternative materials – Hazardous and chemical substances should be avoided/restricted in the production of 6G networks. This can be done by complying with the existing regulations on restriction of hazardous substances and chemicals and using alternative materials instead.
- Modular and durable equipment – Modular design of 6G allows for extended lifespan and easier customization and scalability of the system while reducing waste generation and downtime.
- Energy Efficiency – A significant increase in future traffic is expected which subsequently can lead to higher power consumption. Energy efficiency is therefore of importance in the design of 6G technology, in both production and operational phases. Strategies to direct towards energy efficient 6G include the use of low-power components, optimization of network architecture and protocols, implementation of energy-efficient algorithms and use of more renewable energy resources.
- Cloud Computing and Automation – Automated and intelligent system which help to reduce the amount of data or power consumption in the system needs to be considered. For instance, by

moving some of the processing power from the cloud to a location to the end user or the device, through edge computing, total amount of data and total energy consumption of a 6G system can be reduced. Another example is to manage the on/off states of networks and devices to match the demand of the system.

- Circularity practices – Achieving circularity require a fundamental shift in how equipment and devices are designed, produced, used, and disposed of and needs actions from all stakeholders. 6G system needs to adopt circularity practices for instance via the use of renewable energy resources, design of equipment that can easily be recycled or disassembled at their end-of-life and design of equipment that that their components can be reused, refurbished, recycled, and repaired.

3.2.2 Social sustainability

Social sustainability is comprised of two main aspects: Trustworthiness and digital inclusion. The following social sustainability aspect needs to be considered when designing 6G technology.

- Cyber-secure and respect end-users' privacy – 6G solutions, devices and networks need to be cyber-secure and respect end-users' privacy.
- Transparent AI-based approaches – AI-based approaches need to be clear, transparent. It should also keep the human in the loop. These aspects enable accountability, and thus trust, can be maintained.
- Flexible capacity and coverage – 6G networks need to adjust capacity and coverage depending on geographical areas and the end-users' needs. It is also important that the 6G networks is flexible to adjust to the criticality of the offered solutions, e.g., e-health aspects vs. entertainment.
- Non-discriminatory – 6G solutions, including devices, need to for e.g., consider IT literacy and culture of all types of end-users.
- Ensure coverage and capacity at certain level – This helps to maintain people's trust in digital capabilities and services.

3.2.3 Economic sustainability

6G technology design needs to also incorporate economic sustainability considerations. The following drivers and goals are identified from economic sustainability perspective for 6G.

- Value-based 6G design – 6G should be designed such that it brings economic value beyond users/buyers. It should provide opportunity for different stakeholders to harness converging technologies to create an inclusive, human-centred future.
- Sustainable 6G business model innovation – 6G should be developed to solve major sustainability challenges while being sustainable. Sustainability will be the source of value and sustainability can become the core of future business models.
- Open value configurations via 6G – 6G needs to be developed encouraging innovation via open value configurations. It should share economy models which allows stakeholders to innovate and create new collaborative business models for the whole 6G ecosystem while considering security concerns.
- Sustainable competitive advantage via correlated/holistic sustainability perspective in 6G – 6G development needs to identify the complex interdependencies and trade-offs between the three sustainability pillars, i.e., environmental, social, and economic sustainability. This is to develop a new correlated sustainability perspective to reach long-term competitive advantage in the new 6G ecosystem.
- Monetizing with 6G in challenging business environment – 6G needs to bring return on investment in different environments including supporting the varying density of users, data, and energy usage. As this monetization should be achieved while operating under increasing environmental sustainability requirements, different business models are called for.
- Preparing for mitigating risks with 6G – By 2030, the time of launching 6G, environmental risks such as climate action failure as well as social risks such as geoeconomic confrontations, digital inequality and cybersecurity failure will have potentially big impact on the economy of nations, companies, and individuals. It is therefore important that 6G development and deployment prepare for protecting stakeholders from the increasing risks in the changing operational environment related to environmental, social, and business aspects among others.

4 Device classes

From the use-case analysis in Chapter 2, it is evident that a single use-case may be served by multiple devices and possibly belonging to different device classes. In this document, most of the analysis is based on the [HEX223-D11] use cases. The upcoming Hexa-X-II deliverables, such as D1.2, aims to propose an enhanced methodology for analyzing the use cases and identifying the limitations of current technology etc. This new analysis could have an influence on the identified device classes in this document, resulting potentially in new device classes such as the ones related to the enhancements of URLLC and eMBB types of devices in 5G. This is noted in Chapter 5 and is planned along with joint sensing and communication aspects to be elaborated further in a later deliverable from the Work Package 5 and based on the upcoming Hexa-X-II deliverables.

We have defined an exhaustive set of the characterization criteria in Chapter 3, which is organized into groups. Among the groups of characterization criteria, we attached more weight to ones from energy and communication/radio performance to determine distinct device classes, which is summarized in Table 4-1. This gives a good overview of the parameters that impact the energy and (radio) performance of the end-to-end system. In Table 4-1, relative indications (very low – low – medium – high - ultra) are used to depict the distinction between the device classes. For latency, reliability and availability, the transition from medium to ultra is one order of magnitude tighter per each higher step. For e.g., ultra has 99.999% reliability while high would translate to 99.99% and medium would translate to 99.9% reliability. As noted in [HEX23-D14], the literature study indicates variations between the numbers for the mentioned criteria among similar use-cases and exact values depends on the use-cases, how the solution is architected etc.

Table 4-1: Device classes overview

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 (lowering energy consumption could take precedence over reliability)	As 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

In Table 4-1, *Energy Neutral (EN)* device class represents very low data rate devices that function based solely on harvested energy. Zero energy devices, a device type that is identified in the use-case section, are mapped into energy neutral device class. *Reliable High Data Rate with Bounded Latency* (RHDRBL) device class refers mainly to devices that enable immersive experiences such as XR devices. These class of devices needs high data rates and bounded latency (= consistent low latency) more in the order of tens of milliseconds yet at some amount of reliability (for e.g., 99.9%). These reliability requirements are not as high as the *High Reliability and Low Latency* (HRLL) class of devices, which is mainly about devices in the Industrial IoT domain. The devices in the HRLL device class would typically need reliability around 99.99% and latency of about 1-10ms range. Therefore, they have more relaxed requirements than the *Ultra Reliable and Low Latency (URLLC)* devices in 5G, which are typically defined to have 99.999% reliability at 1 ms latency for 32 bytes packets [LSK20]. Finally, the *enhancement of mMTC* device class aims to provide enhancements to Low

Power Wide Area Network (LPWAN) devices, focusing mainly on power consumption, slightly higher data rates than in the 5G time frame, and maybe on the reliability requirements. It is good to note that some indicative numbers are available within the respective device class sections and depend on the specific deployments.

The rest of this chapter is organized as follows. Each of the identified device classes is elaborated for their 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) and their technology enablers (technologies that help to realize devices within that device class). Furthermore, system / infrastructure enablers (if any) that will support the devices to be integrated in a 6G system and sustainability considerations that could be relevant to a class of devices is also described. Where possible to have consistent numbers backed with references, the key performance parameters are detailed with these numbers. Finally, a link to the use cases for each device class and examples of devices that belong to a specific class of devices are provided.

4.1 Energy neutral device class

Energy Neutral (EN) devices are energy harvesting IoT devices that embody an ultra-low energy consumption and demand throughout the entire life cycle (from manufacturing to disposal), facilitate zero waste generation, and embraces material circularity principles.

The key energy-related principles of EN IoT devices are:

- Energy-efficient design and operation: Operation must be designed to minimize energy consumption, e.g., by optimizing hardware components, reducing power requirements, and utilizing low-power/sleep modes.
- Energy-conscious manufacturing: The manufacturing must leverage green practices and technologies, e.g., using energy-efficient/green equipment, optimizing production processes, and low-cost, circularity, and biodegradable materials.
- Energy-aware deployment: The deployment must maximize energy efficiency considering short and long-term impacts. For instance, the devices may be deployed such that their exposure to energy sources for harvesting and their sensing/transmissions capabilities are properly balanced considering time-varying environment/network/device conditions (e.g., seasons, coexisting networks/devices, hardware aging from the environment, network, and device perspective, respectively).
- Energy-frugal disposal: Recycling, repurposing, and biodegradability practices must be promoted to minimize energy consumption associated with disposal and reduce waste generation.

Zero-energy devices, a device type identified in Chapter 2 maps to this device class. Some deployment scenarios include but are not limited to asset tracking, transportation & logistics, warehouse, industrial (e.g., factory automation, harbors, docks), stores (e.g., automatic inventory), or smart home.

Figure 4-1 depicts the placement of EN devices in the IoT device landscape.

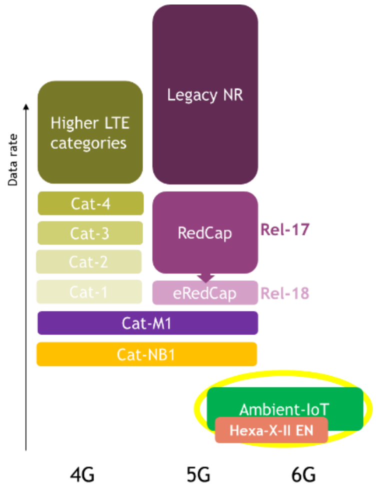

Figure 4-1: Placement of EN devices in the IoT landscape

4.1.1 Key characteristics

EN Operation

The EN operation consists of following aspects:

- Energy harvesting (self-sustained): The suitable energy harvesting source depends on the requirements of the specific use case and environment [LRR+23]. Refer to Table 4-2 where different energy sources are listed together with typical characteristics and potential use cases.
- Energy storage: The harvested energy can be stored to re-chargeable Li-ion batteries, thin-film batteries, super-capacitors, or conventional capacitors. Rechargeable batteries are preferred for high-energy sources, active devices, and large form-factors, and incur high-cost. Devices with limited energy storage capability (e.g., capacitor network) may be appealing for mid-energy sources, passive or semi-passive devices, and small-form-factor devices, and may have a relative lower cost. Meanwhile, battery-less implementations fit better for low-energy sources, passive devices, and small-form-factor, and are intrinsically much cheaper. Note that these features are described in relative terms, allowing for a qualitative comparison/guideline rather than specific quantitative measurements.
- Energy management: Efficient energy management mechanisms must be implemented at different levels, including circuit and protocols, to guarantee EN operation [LRR+23]. For instance, duty-cycling at both transmission (Tx) and reception (Rx), energy-aware selection/adaptation of parameter settings for uplink and downlink transmission, and energy-aware scheduling are appealing.

Table 4-2: Typical energy sources for EN IoT devices, and corresponding characteristics and potential use cases (cf. [LRR+23] and references therein).

Energy Source	Power Density	Form Factor	Limitations	Use Cases
Light	17 mW/cm^2	medium/ large	sensitive to blockage	remote applications, outdoor sensors
Heat	10 mW/cm^2	medium	sensitive to thermal stress	wearables, infrastructure monitoring
Microbial fuel cells	5 mW/cm^3	medium	limited stability/lifespan	smart farming, wastewater treatment
Vibration	20 mW/cm^3	small	sensitive to mechanical fatigue	wearables, infrastructure monitoring
RF	10 nW/cm^2	very small	very low output power	ultra-low power devices

Low complexity, cost, and form factor

EN devices would have lower computation capability, cost, and data rate than mMTC type devices, including NB-IoT. Also, relatively small-form factors are desired for imperceptible deployment.

Low mobility

The devices can be static, e.g., in indoor scenarios or with low mobility, e.g., in outdoor scenarios with asset tracking. As the devices are extremely limited, thus mobility solutions based on cell reselection would be beneficial due to its least overhead.

Lifetime spanning from a few months up to many years

EN devices with short-lifetime (e.g., a few months/years) may fit applications such as tag-like or smart logistic/warehouse devices, which are discarded when required procedures are completed. For these, biodegradable materials may be the most lifetime limiting factor.

EN devices with long-lifetime (e.g., >10 years) may require reconfiguration capabilities and coexistence support for operation with future generation networks. For these, the energy storage device characteristics/performance may be the main lifetime limiting factor.

In general, there might be different EN sub-classes depending on groups of common characteristics, probably with a common supporting protocol stack.

4.1.2 Other characteristics

Synchronization

No tight synchronization (receiver-initiated communications) is required, enabling support of low-accuracy receivers in a flexible manner. The active devices can have a larger (frequency or time) synchronization error threshold than existing 5G devices.

Data rate

Low-data rate. The specific figure depends on the application, energy availability, and radio capabilities. Typical values for backscattering are within 10 bits/s and 1 kbit/s - backscatter symbol length and frequency need to be selected such that the receiver channel estimator and equalizer can track it, if necessary.

Security

The device must employ security by 6G core networks and additional low complexity 6G radio access network (RAN) security, which may be complimented depending on solution and RAT type. Security may be assisted by positioning information when available, e.g., to make sure the device is in its intended place of operation. Additionally, the security and authentication of carrier wave emitters must be considered while transmitting over backscattered link.

Spectrum

To support wide coverage (especially for active EN devices) and low power consumption, primarily the licensed low spectrum bands are considered. However, passive exploitation of unlicensed spectrum may be possible, e.g., for RF energy harvesting).

Waveform

Simple waveforms, preferably compatible with orthogonal frequency-division multiplexing (OFDM) are to be utilized. Modulation can be active (wherein the devices generate their own RF signals) or passive (wherein devices rely on reflecting or modulating an incoming RF signal from a reader or base station to transmit information) depending on the device/application. Envelope detection may be appealing for ultra-low cost/energy devices.

Low-overhead/signaling and energy-aware protocols

A minimized protocol stack is needed at RAN/CN level as the device is not expected to serve traffic with strict quality of service (QoS), packet delay budget (PDB), reliability target and heavy payloads. The protocols can be devised taking into considerations energy-aware operations and limited computation capabilities, etc.

Predefined reliability/availability support levels

Such levels, if any, are mostly low and depend heavily on the availability of the energy sources and the energy management performance. They are in-line with the specific use case requirements and may correspond to the probability of successful transmission/reception.

Configuration

Configuration information is needed whenever a device needs to access the cell or network, which could be related to downlink signal reception or performing uplink transmission. Relaxing the requirement for configuration or system information acquisition depending on the use-case, may to energy savings, i.e., devices with energy saving capability can acquire system information when required compared to passive devices which will only acquire system information when enough energy is available.

4.1.3 Technology enablers

It is important to note that not all the technical enablers are suitable for every device in this class. Hence their applicability can depend on use-case, application, device capability, harvesting infrastructure, etc.

Low-overhead/signaling and energy-aware protocols

A minimized protocol stack is needed at RAN/CN level as the device is not expected to serve traffic with strict QoS, PDB, reliability target and heavy payloads. The protocols can be devised taking into considerations energy-aware operations and limited computation capabilities.

Low-cost, circular, and/or biodegradable manufacturing technologies

Manufacturing can utilize printed electronics, cellulose based or other biodegradable substrates and recyclable materials. For instance, printed electronics + radio-frequency identification (RFID) chip (sustainability depends on packaging of the chip) hybrid designs for devices with chip, while antenna and RF components can be printed for devices without chip.

Backscattering

Backscattering technology utilizes existing RF signals (as a carrier) for modulation without generating carrier at the device, offering energy-efficient options for low-power IoT devices with potential benefits in battery life extension and device design simplicity [LRR+23]. A pure backscattering device may be unable to process downlink and security apparatus would be limited. Advanced designs may include a low complexity receiver for the reception of signalling and downlink data.

Energy management mechanisms

Energy harvesting forecasting methods and management mechanisms can be useful as the devices may not have guaranteed energy supply all the time. For instance, the net energy, which can be calculated by subtracting the energy consumption from the total harvested energy, may be tracked, and minimized for devices with energy storage. Other examples can include dynamic voltage scaling, sleep modes, and duty cycling [LRR+23], etc. Methods to forecast energy harvesting are appealing. Also, net energy which can be calculated by subtracting the energy consumption from the total harvested energy may be tracked and minimized for devices with energy storage.

Computation offloading

Computation offloading involves transferring computing tasks to remote servers, optimizing EN device performance by leveraging external processing capabilities. This technology can lead to improved efficiency and responsiveness in resource-constrained environments, but offload vs local computation trade-offs are device/scenario-dependent and must be properly assessed case by case. The overhead can be higher if special interface is needed between the EN device and the node to which data being offloaded, which will add to the configuration cost.

Intermittent computing

Intermittent computing may support the intermittent operation of EN IoT devices with irregular or intermittent power sources. The technique relies on asynchronous operation and prioritizes tasks based on importance, allowing the devices to function efficiently and extend their operational lifespan in remote or power-constrained environments. A key example is intermittent computing based on checkpointing, which allows to periodically save volatile states in non-volatile memory so that the program execution can restart from a known state if the power supply fails.

Wake-up radio

Wake-up radio utilizes low-power signals (from the network) to trigger device activation from a low-energy state, enabling efficient communication and minimizing overall power consumption in low-power IoT networks [LRR+23]. This may increase complexity as it requires additional radio implementation.

Low complexity localization and sensing

Proximity-based localization using beaconing enhances the security of low-power IoT nodes by enabling device detection/sensing, access control, intrusion detection, geofencing, secure pairing, and tamper detection. It allows IoT systems to make informed security decisions based on the proximity and identity of nearby devices, contributing to overall security and reliability in IoT deployments.

Tiny ML

Very low-complexity ML can be desired, which performs computations at extremely low power, and this may be appealing for energy management and/or energy efficient computation/scheduling of application resources [KPR+23], [LRR+23]. The application does not have direct influence on the network design, but it can improve the targeted application performance. However, the cost would be the utilization of computation resources for the device and may be useful for some device categories in the EN class which can afford some computation complexity.

4.1.4 System/infra enablers

Data buffering

EN device can utilize core network (CN) level data buffering which will serve multiple purposes i.e., it avoids RAN resources being reserved for extended period and avoids the scenario where EN device has moved to another RAN and data is buffered at another. The buffered data in CN can be made more situation aware by having an additional parameter i.e., age of information or expiration of information (implying the duration for which the DL data is useful for the EN device, after which it can be discarded from CN buffer). It will enable EN device to receive relevant information whenever it is reachable and save resources for both the device and the network.

Helper node

The helper node is an infrastructure enabler device and can assist a 6G cell’s controller node which is serving EN devices by managing their transmissions to some degree. The EN device has intermittent receiver activity because of lack of consistent power or energy storage capability. Therefore, the infrastructure enabler device can help the controller node in buffering transmissions which are meant for EN device when EN device’s receiver is inactive. This can enable a controller node to improve its load capacity. This may not be an issue with a cell serving one or few EN devices, but this can become a potential issue, if we consider scenarios with 100s or 1000s of EN devices (tags, stickers), e.g., tags attached to products in a warehouse which are receiving downlink updates consistently. The infrastructure enabler device's operation can be configured by considering EN device’s receiver activity or operational cycle. One example is to configure duty cycling (also known as discontinuous reception (DRX) in some standards) settings at infrastructure enabler device in such a manner that its control channel monitoring period occurs when EN device’s receiver is inactive. During this period, infrastructure enabler device can receive EN device’s transmissions and buffer them, and after some time, when EN device’s receiver becomes active, the infrastructure enabler device can transmit all the buffered transmissions. Both infrastructure enabler and EN devices are visible and controlled by the 6G network which is important especially dealing with use cases involving EN devices because of two reasons:

- it is not possible for EN device to sacrifice or invest resources in sensing due to limited power/energy capabilities in absence of central authority or controller node,
- for synchronization (for instance, related to DRX configuration) between an infrastructure enabler device and one or more EN devices, the controller node can easily configure or synchronize various nodes as all these nodes are fully controlled by controller node.

Hence, the utilization of infrastructure enabler device can ease the management control at controller node which is handling large number of EN devices by offloading the transmissions to infrastructure enabler device.

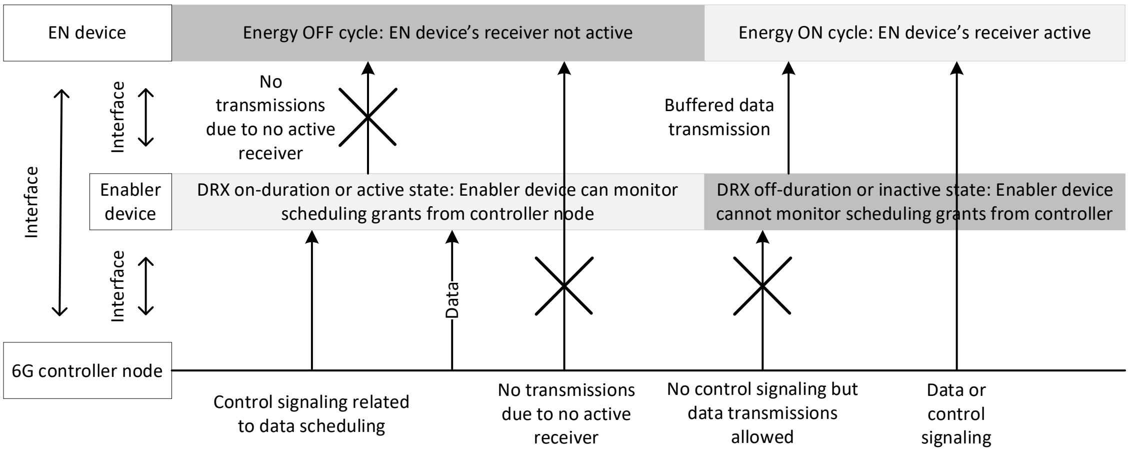

Figure 4-2: Role of an Infrastructure enabler device as system enabler for EN devices.

EN backscatter devices can be integrated to mobile communication systems without the need for new hardware by using receiver channel estimator as a receiver. This is possible because the receiver sees EN backscatter device (BD) as an additional multi-path component. Backscatter device and introduce artificial Doppler to the channel allowing the receiver channel estimator to separate natural multi-path components from the EN backscatter modulated path in frequency domain [LWR+23]. The bandwidth available for the backscatter system is limited by the rate at which the cellular system transmits reference signals. To improve the data rate of EN backscatter devices, the new reference signals could be defined to allow more frequent estimation of the channel. Figure 4-3 illustrates how the reference signals generated by mobile communication system could be utilized to read EN backscatter device modulated messages at the receiver channel estimator.

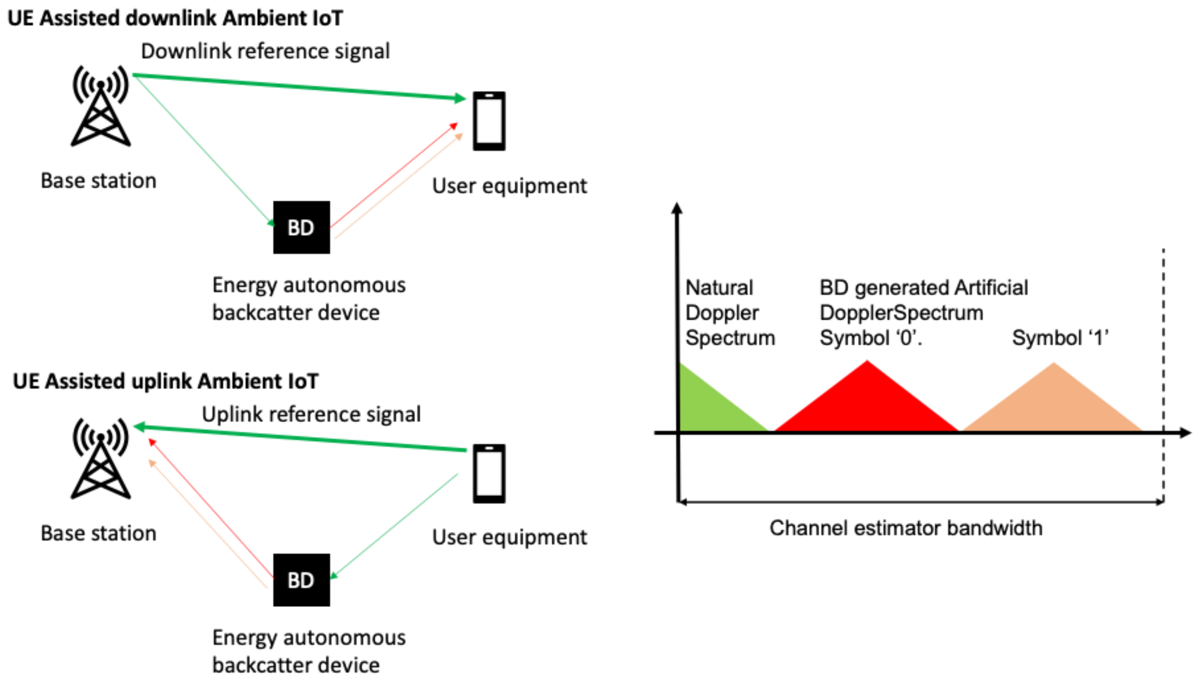

Figure 4-3: Using cellular infrastructure to read EN backscatter modulated messages.

Radio frequency (RF) wireless energy transfer (WET)

As infra-enabler, RF-WET provides a controllable and predictable RF energy supply. High availability may require dedicated WET.

The main goal in RF-WET must be the joint end-to-end conversion efficiency optimization since the nonlinear response of the RF-WET components, i.e., the energy transmitter (hereinafter, refer to as power beacon (PB)), the channel, and energy harvesting (EH) circuit, couples the overall system performance. The PB can be a 6G base station that provides both wireless communication and charging services [LAS+21].

For PB implementations, low complexity and low energy consumption architectures are crucial. In this regard, one can rely, for instance, on analogue/hybrid beamforming architectures, low-resolution phase shifters and digital-to-analog converter (DAC)/analog-to-digital converter (ADC), and lens antenna arrays [RLA+23]. Notice that RF-WET is fundamentally different from traditional information transmission, which hence opens the opportunity for hardware-oriented designs considering, for instance, that interference is no longer an enemy in these RF-WET systems and that high peak-to-average power ratio signals boost the EH conversion efficiency. Further, the RF-WET infrastructure can be supported by a network of self-sufficient PBs capable of harvesting energy from ambient resources and autonomously trade energy with peers when that is insufficient [LAS+21], [RLA+23].

The distance-dependent loss is a key limiting factor of the end-to-end conversion efficiency. Fortunately, passive reconfigurable intelligent surfaces (RIS) assist in reconfiguring the propagation environment to overcome obstacles and extend the RF-WET coverage with minimum additional costs/energy consumption. Further, one can rely on nomadic RF-WET implementations in which unmanned aerial/terrestrial vehicles act as a PBs. Notice that this implementation can dynamically reduce the charging distance and therefore boost the efficiency.

The last component of the RF-WET chain is the RF-EH circuit. To boost its conversion efficiency, a natural first step can be to equip the receiver with multiple antennas, However, notice that EN devices are by nature hardware-constrained devices in terms of computation and energy capabilities. Consequently, EN devices cannot be involved in the computationally/energy demanding process of estimating the instantaneous channel state information. Moreover, multi-antenna implementations allow more flexible designs of the RF-EH receiver as one can dynamically combine the receive signals in different domains (i.e., RF, direct current, or hybrid) to boost the received signal power [LAS+21].

4.1.5 Sustainability considerations

The sustainability considerations for the EN device class are grouped under the following three sustainability pillars:

Environmental sustainability

- Ultra-low energy consumption and demand throughout the entire life cycle, from manufacturing to disposal.
- Using renewable energy sources and biodegradable or recyclable materials whenever possible.

Social sustainability

- Promote digital inclusion and well-being by providing enhanced wearable and in- or on-body sensor and corresponding services.
- Social equity and well-being by providing for instance safety and security measures under environmental hazard and security condition.
- Avoid data leaks, and thus preserve data privacy.

Economic sustainability

- Optimizing resource usage and efficiency resulting in improving maintenance procedure.

4.1.6 Key performance parameters

The following are the key performance parameters for the EN device class.

Ultra-low energy consumption

The primary sources of energy consumption typically include wireless communication (transmitting and receiving data), computation (processing data and executing algorithms), and sensor operation (collecting and processing environmental data). EN devices may have limited capabilities in terms of communication, computation, and/or sensing to limit energy consumption, costs, and form factors. The existing capabilities must be optimized, along with managing sleep modes and duty cycles, to achieve overall energy efficiency.

Highly efficient energy harvesting

Energy-harvesting capabilities may be location-dependent, as the availability of the energy sources may vary accordingly. Therefore, in very simple systems, deployment optimization is crucial. In more complex systems, efficient energy management techniques may suffice. In any case, the energy harvesting circuits must be optimized for maximum efficiency. Efficiency degradation over time, e.g., due to the degradation of materials, wear and tear, or contamination, must be considered.

Low energy consumption per successful transmission

EN devices must be engineered to operate efficiently in environments with a high density of interconnected nodes, ensuring minimal interference and spectral occupancy. For doing so, they must employ lightweight and energy-aware communication protocols, spectrum utilization techniques, and channel access mechanisms. EN IoT devices may contribute to the establishment of scalable networks, enabling widespread deployment and effective collaboration among a multitude of devices while maintaining stringent power constraints. Therefore, in addition to data transmission at low energy consumption, leveraging energy efficient/aware MAC or similar technologies, such transmissions should have a high probability of success in a dense environment.

4.1.7 Link to use-cases

EN devices assist many use-cases, such as, E-health for all, autonomous supply chains, earth monitoring. The devices can work in conjunction with other IoT, NTN, eMBB and XR devices to support the uses cases. The requirements of use case can influence the EN device integration - passive, semi-passive or active EN device.

4.1.8 Example devices

The devices can appear with varying form factor and hardware/electronics (backscattering or harvesting or combination based). Examples are tags, stickers, in- or on-body sensors.

4.2 Reliable high data rate with bounded latency devices

The reliable high data rate with bounded latency (RHDRBL) device class provides immersive experience, through mixed, augmented, and virtual reality. With high guaranteed data rate, reliability and bounded latency demands, it ensures quasi-realistic virtual experience for merging cyber and physical worlds. This class supports diverse communication needs and encompasses different functions such as visual devices/headsets/glasses as well as wearables and haptics, ensuring seamless integration with various devices. The following are some definitions of the main devices in this device class [26.928], [38.838]:

- **Extended reality (XR)**: represents real-and-virtual environments combinations as well as interactions between humans and machines. It is a generic term that encompasses for AR, MR and VR which will be explained later. It also considers all the fields interpolated between these terminologies. The degree of virtuality cover a wide spectrum from partially sensory inputs to fully immersive VR. The main goal of XR is to extend the experiences of humans regarding the senses of existence (which can be achieved by VR) and the acquisition of cognition (which can be achieved by AR).
- **Virtual Reality (VR)**: given some delivered audio and video data, a virtual reality rendered version is delivered to the user. This rendered version is designed to quasi replicate the visual and audio sensory data received from the real world to a certain limit defined by the application. VR applications often require the user to use a head mounted display (HMD), to replace the user field of view with the rendered visual components instead of real world. Also, headphones are needed to enrich the VR experience with accompanying audio. Moreover, head and motion tracking sensors provide better reactivity for visual and audio components to be accurately updated and synchronized with the VR user movements.
- **Augmented Reality (AR)**: represents the overlay of additional artificially generated items or contents on top of the real environment. This additional content is mainly a visual and/or audio content that can be directly relative to an observation from the surrounding or indirectly through additional perception of the environment through sensing. In the case of indirect reaction to the environment, additional sensing, processing, and rendering may be needed.
- **Mixed Reality (MR)**: is an evolutionary version of AR in which some elements can be added virtually into the real environment that leads to an illusionary view that these elements exist physically in the real environment.

4.2.1 Key characteristics

Device class where applications need high (guaranteed) data rate with bounded latency; high availability and device orientation & location accuracy influences QoE.

Quality-of-Experience for XR devices mainly depends on the following factors which are immersiveness and presence and interaction delays and age of content, which can be explained in more details as follows [26.928], [38.838]:

Immersiveness and Presence: immersiveness and presence encompasses the sensation of being physically and spatially situated within a particular environment. This concept can be categorized into two distinct types:

- **Cognitive Presence**: pertains to the presence of one’s mental faculties. It can be attained through activities such as engrossing film-watching or captivating book-reading. Cognitive presence holds significance for creating an immersive experience in various contexts.
- **Perceptive Presence**: relates to the involvement of one’s sensory perception. Achieving perceptive presence involves the manipulation of one’s senses, including sight, sound, touch, and smell. To establish perceptive presence, XR devices must effectively deceive the user’s sensory perception, particularly the visual and auditory systems. XR devices accomplish this by employing positional tracking based on the user’s movements. The primary objective of this system is to maintain the user’s sense of presence without disrupting it.

Presence is attained when the instinctual elements of our primitive brain regions are triggered. There are four key elements that contribute to the sensation of being present:

- The illusion of being in a stable spatial place

- The illusion of self-embodiment
- The illusion of physical interaction
- The illusion of social communication

The most crucial aspect from a technical standpoint is the first element. This facet of presence can be subdivided into three general categories, ranked in order of their significance in shaping presence:

- Visual presence
- Auditory presence
- Sensory or haptic presence

Visual presence requires the following:

- Tracking: 6DoF tracking (where 6DoF or 6 degrees of freedom, represent the 3D position and the rotation of the device), 360 degrees tracking (where 360 degrees tracking defines the ability to track the user's head regardless of the direction the user is pointing at), sub-centimeter accuracy, quarter-degree-accurate rotation tracking, no jitter, comfortable tracking volume, above 1000 Hz tracking frequency (where tracking frequency defines how often the device needs to relate its current location to a prior one for accurate tracking).
- Latency: < 20 ms motion-to-photon latency, where motion to photon latency defines the delay from the time you move your head to when you see the display change. To meet that 20 ms, it does not necessarily mean the 6G round-trip needs to be extremely low. Intelligence on the device can help achieving these using techniques such as asynchronous time warping and space warping.
- Persistence: Low persistence - Turn pixels on and off every 2 - 3 ms to avoid smearing / motion blur; 90 Hz and beyond display refresh rate to eliminate visible flicker.
- Resolution:
- Spatial Resolution: No visible pixel structure - you cannot see the pixels.
- Temporal Resolution: a sustained frame rate of 90 Hz and beyond.
- Optics: Wide Field of view (FOV) is the extent of observable world at any given moment and typically 100 - 110 degrees FOV is needed; Comfortable eyebox (eyebox defines the volume where the eye receives an acceptable view of the image); High quality calibration and correction - correction for distortion and chromatic aberration that exactly matches the lens characteristics.

The sense of presence holds significance not only in VR but also in immersive AR. To establish a sense of presence in AR, it is crucial to seamlessly blend virtual elements with the physical environment. Just as in VR, the virtual elements must align with the user's expectations. In the context of truly immersive AR, especially MR, the goal is for the user to be unable to distinguish between virtual objects and real ones.

Noteworthy for both VR and AR, with particular emphasis on AR, is the importance of considering not just the user's experience but also the awareness of the surrounding environment. This encompasses:

- Safe zone discovery
- Dynamic obstacle warning
- Geometric and semantic environment parsing
- Environmental lighting
- World mapping

In the realm of AR, to improve their perception of the actual surroundings, individuals might utilize HMD to observe three-dimensional computer-generated objects overlaid onto their real-world perspective. This see-through functionality can be achieved through either an optical see-through or a video see-through HMD.

Interaction Delays and Age of Content: Beyond the aspects of presence and immersion, the age of content and the delay in user interaction are paramount considerations for both immersive and non-immersive interactive experiences, such as those found in online gaming. The user interaction delay, age of content, and round-trip interaction delay, are defined as follows:

- **User interaction delay**: refers to the time elapsed between when a user initiates an action and the when the content creation engine acknowledges and incorporates that action. In the gaming context, this delay represents the time between a player's interaction with the game and when the game engine processes and responds to the player's input.

- **The age of content**: on the other hand, signifies the duration between when the content is initially generated and when it is presented to the user. In the context of gaming, this duration encompasses the time between the creation of a video frame by the game engine and when that frame is ultimately displayed to the player.
- **The round-trip interaction delay**: it comprises the combination of both the age of content and the user interaction delays.

4.2.2 Other characteristics

Device class where applications need high requirements on computation, traffic and benefits from AI enabled compute engine, given device limited form factor.

XR traffic has strict QoS requirements:

XR traffic has strict QoS requirements such as bounded-latency, high data rate and reliability requirements. XR traffic requires strict motion-to-photon latency - <20 ms of overall latency (motion to photon latency defines the delay from the time you move your head to when you see the display change). Also, XR traffic requires significantly high data rates that can reach few Gbit/s for DL flows while maintaining reliability constraints of 99.9%, which means that the loss rate of packets transmitted end-to-end (E2E) across a network should be less than 0.1%.

XR traffic frame multiple quasi-periodic DL and UL flows:

The XR traffic is represented by a sequence of frames arriving at a receiver node from a transmitter node, according to a given traffic frame rate/periodicity. It also has a random variation in time which is defined as jitter. The size of each data frame, in the sequence of frames, also variates according to a certain random distribution. The typical XR traffic frame size and jitter are modelled by truncated Gaussian distribution [38.838]. XR traffic has variable frame sizes that can be modelled by a truncated gaussian distribution to capture the variation in bytes between different frames. Also, beside the XR traffic cadence and periodicity requirements, frames can arrive with some variation in time which is modelled by truncated Gaussian distribution as well. Moreover, XR typical traffic packet generation rate does not match the 6G slot granularity. The XR packet arrival rate is determined by the frame generation rate, e.g., 60 fps. Thus, the average packet arrival periodicity is given by the inverse of the frame rate, e.g., 16.6667 ms = 1/60 fps, where fps is the number of frames per second, and it represents the frame arrival rate. This non integer value of packet arrival rate causes the mismatch with 5G RAT slot granularity. The current NR slot granularity is dependent on subcarrier spacing (SCS) as follows: for SCS of 15, 30, 60, 120, 240 kHz, the corresponding slot durations are 1, 0.5, 0.25, 0.125, 0.0625 ms respectively. Thus, mechanisms defined in 6G need to be compatible with such cadence (for example with enhanced CDRX or other approaches).

Computation (Standalone/direct link to network, via an (intelligent) aggregator)

XR devices can apply local compute for processing/rendering at the device itself. However, this can induce higher latency, more power consumption and lower QoE. 6G capabilities can ensure high data rate – low latency communication links to the edge compute servers. Hence XR devices can leverage computing power from the edge compute server for graphics rendering, through connecting to these servers directly over 6G or through an intelligent aggregator.

Device Capabilities:

This device class is characterized by small form factor, limited battery size, expectation of long duration wearability. Some XR devices will not be capable of deploying four receive antennas at low frequency bands due to form factor limitations. Therefore, some two receive devices with co-polarized antennas will need to cope with the high data rate-bounded latency-high reliability requirements over 6G. This can be achieved by fixing the UE BW to 100 MHz for these 2Rx limited form factor devices and considering their special device characteristics and KPIs that need to be achieved over 6G.

4.2.3 Technology enablers

AI as a service

AI and ML have made a significant impact on nearly every industry, pushing the boundaries of what high technology can achieve. In the context of XR services and delivering XR wirelessly, there are two crucial types of intelligence required to ensure effective and efficient performance: service intelligence and operational intelligence. Service intelligence is essential for tasks directly related to the XR application itself. This encompasses ML processes that handle rendering actions associated with the VR scene and the coordination of multiple holograms. On the other hand, operational intelligence equips the network with intelligent mechanisms to optimize and sustain complex services like XR, ensuring their smooth operation and self-sufficiency.

Perception

It facilitates enhancing the device awareness by applying inferencing methods applied to a collection of sensor and wearable data. For example, the perception is responsible for estimating the motion and the environment such that the metaverse content can be rendered to reflect the user’s movement and the environment.

Spectrum

It utilizes FR1, FR2, and potentially operate also in centimetric range and sub-THz bands for different objectives (capacity/coverage, data rate, etc.): A good XR user experience requires high data rates, high-reliability, and low/ultra-low latency simultaneously. FR1, although reliable and ideal for mobility, cannot provide high data rates and ultra-low latency rates. The mmWave and sub-THz bands can fulfil data rates and latency requirements but are limited in range and mobility. It is good to note that considering these trade-offs along with the deployment scenarios would be helpful in optimizing sub-THz transceivers, whose design aspects are covered in Appendix A. Also, operating at centimetric range can provide a good trade-off between coverage and capacity.

Energy optimized services

It is required for users who want to add additional attention to energy consumption.

4.2.4 System/infra enablers

Edge computing

XR system can leverage computing power from the edge compute server for graphics rendering. With edge computing, user can access services hosted close to the serving 6G network entity. This approach helps to improve both end-user experience and network efficiency. Lower latencies can improve end-user experience, while reduced backhaul transport requirements can improve network efficiency.

4.2.5 Sustainability considerations

The sustainability considerations for reliable high data rate with bounded latency device class are grouped under the following three sustainability pillars:

Environmental sustainability

- XR and other devices enabling fully merged cyber physical worlds 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

- Using Mixed Reality (MR) devices for virtual medical consultations can improve the access to healthcare and removes the distance barriers between the patients and the doctors (“access to quality health-care services”),
- Improve teaching quality and availability through providing mixed reality access between teachers and students (aided by MR devices), while removing the distance barriers (“access to education”).

Economic sustainability

- XR devices, for example, 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").

4.2.6 Key performance parameters

Several performance metrics need to be satisfied for XR devices [38.838] such as:

- Latency: The latency requirement of XR traffic is modelled as packet delay budget (PDB). The PDB is a limited time budget for a packet to be transmitted over the air from a 6G network entity to a user. XR devices require <20 ms PDB.
- Cell Capacity: is defined as the maximum number of users per cell with at least Y % of UEs being satisfied. A UE is satisfied if all the considered streams meet their own PDB requirements, i.e., more than a certain percentage of packets are successfully transmitted within a given air interface PDB. To maximize the coverage of XR devices over 6G, cell capacity should be maximized.
- Data Rate: XR devices requires significantly high data rates over 6G that can reach few Gbit/s for DL flows.
- Power Consumption: XR devices require low power consumption over 6G to ensure longer battery lifetime, low thermal dissipations, and long duration of wearability.

The following Table 4-3 indicates the values for some of the key performance indicators.

Table 4-3: KPIs for reliable high data rate with bounded latency devices [38.838] [HEX22-D13].

KPI	Target Value	Reasoning/Reference
Availability [%]	99%	It defines the probability that the system is operational when a demand to access the service is made. It is calculated as: Uptime / Total time (Uptime + Downtime). This device class needs acceptable availability of 99%.
Reliability [%]	99.9%	It represents the packets' loss rate which are transmitted end-to-end across a network. Strict reliability requirement of 99.9% is needed, yet more relaxed compared to URLLC.
Latency [ms]	<20 ms	Combined E2E roundtrip for both UL and DL should be kept below 20 ms. E2E delay is defined as the time needed for a piece of data to be transmitted from a source point to a destination one across the network.
Date Rate	Up to 1 Gbit/s DL 0.1 Gbit/s UL	It defines the typical required data rate to achieve a sufficient QoE for an application that uses this device class. Normally, the application should be able to adapt the data rate based on the radio condition and the loading of the network.
Energy Consumption	Dependent on resolution, frame rates and display technology.	More details are explained in the rest of the subsection.

Energy Consumption: In the process of designing media processing capabilities, XR functionality and integrating network connectivity, it is crucial to have a comprehensive understanding of the energy consumption associated with various components that might be incorporated into XR devices. The following factors should be taken into account [26.928]:

- Tracking and Sensing: 3DoF tracking may require < 1 Watt, while 6DoF tracking requires more power consumption.
- Display: display power consumption in the range of 0.3W to 1W.
- Render (GPU): It can range from several mWatts to several Watts depending on resolution, frame rates and display technology.
- Compute and Media Processing (CPU): similar to GPU, however, encoding may induce higher power consumption.
- Connectivity: Wireless connectivity (for example connection to the network) power consumption can range from several mWatts to several Watts depending on bitrates, distance from radio access network, channel conditions, frequency range, etc.

4.2.7 Link to use-cases

Reliable high data rate with bounded latency devices are the main enabling devices in fully merged cyber physical worlds use case: XR devices and it operates together with other body sensors/actuators (tactile gloves, electromyography (EMG) wristbands, smart watches, smart fabrics, etc.), and smartphone/connectivity puck.

In a scenario involving fully integrated cyber-physical worlds, users will need to engage in communication with individuals located at a distance, aiming for interaction quality that closely resembles real-life experiences. Achieving this level of realism demands an improved understanding of body language, including gestures, intonation, facial expressions, surroundings, and sounds, among other aspects. Additionally, it involves enhancing other sensory perceptions, such as the ability to touch objects, enabling interaction with both physical and digital objects regardless of their proximity in the physical world. This kind of immersive experience use case is enabled using XR devices, as well as wearable devices such as earbuds, and devices integrated in clothes.

4.2.8 Example devices

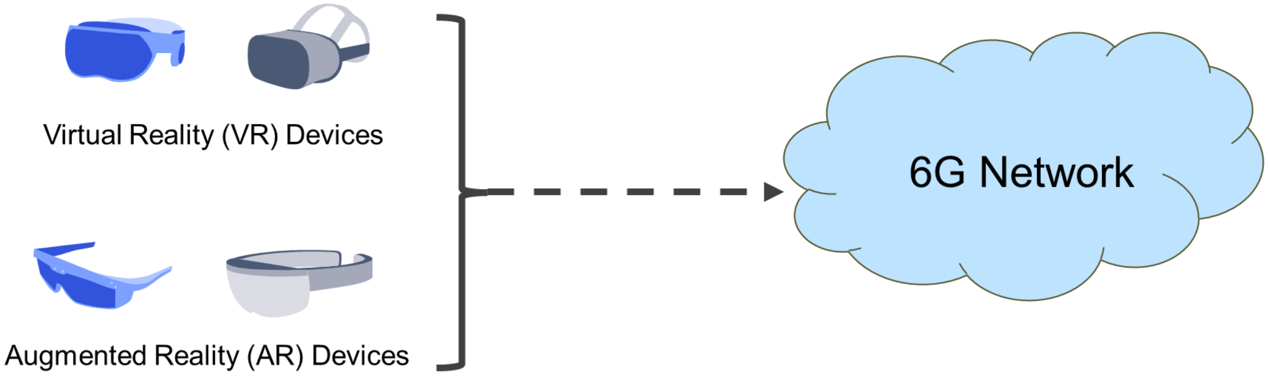

Figure 4-4: Different XR device types.

Extended reality devices are of different types as shown in Figure 4-4. These types may differ in processing capabilities, communication types and power consumption. In AR, the display is usually transparent and digital information is superimposed onto real life objects. In VR, the display is not transparent and only virtual information and images are displayed in front of wearer's eyes.

Also, body sensors/actuators (tactile gloves, EMG wristbands, smart watches, smart fabrics, etc.) can be integrated along with the XR devices.

4.3 Highly reliable low latency device class

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.

4.3.1 Key characteristics

The key characteristics of this device class includes:

Reliability: These devices are characterized by their unwavering reliability. They ensure seamless connectivity and efficient communication through dynamic resource allocation, guaranteeing uninterrupted data exchange. This attribute is paramount for applications that heavily depend on real-time interactions and responsiveness. Whether it's critical data transfer or swift decision-making, the reliability of these devices underpins their effectiveness. Defined by essential features for reliability and effectiveness, as outlined in [HEX23-D14], there is notable variation in reliability figures among different projects. For instance, the human and robot co-working use case demands a remarkable 99.999% reliability and minimal latency of 1 ms.

Autonomy: Operating autonomously in diverse environments is a hallmark of this device class. Their ability to make informed decisions and adapt to ever-changing conditions while maintaining peak performance is remarkable. This autonomy empowers them to navigate complex tasks independently, making them invaluable in dynamic settings where adaptability is key.

Safety: Safety is a paramount concern for these devices, especially when interacting and collaborating with humans. They are designed with an emphasis on safety to ensure cooperative and responsive engagement. This approach fosters an environment where these devices and humans can work harmoniously together, enabling shared tasks and collaborative efforts.

Location Awareness: Another standout feature of these devices is their spatial awareness. They possess the ability to recognize their positions in relation to their surroundings, which enables them to adapt their behaviour based on their geographical context. This contextual awareness empowers them to make decisions and take actions that are not just timely but also relevant to the specific situation, thus enhancing their overall operational effectiveness.

Low Latency: Due to their real-time operational nature, these devices have stringent latency requirements. For example, cobots, which are a prime example of this device class, demand ultra-low latency to enable real-time collaboration. The collaboration between humans and robots, exemplified in the 'human and robot co-working' use case [REI21-D11], tackles safety challenges, high-speed robot movements, and traffic volumes. The data rate is specified per user with high reliability and low latency (1 ms), aligning with Hexa-X's proposed 0.5-25 ms Roundtrip Time (RTT), while 1-50 ms for collaborating robots [HEX23-D14]. Notably, applications extend beyond cobots to include other devices like AGVs in this device class. In industrial settings AGVs rely on low latency to navigate and interact seamlessly within dynamic environments, enhancing overall operational efficiency.

Versatile Connectivity: These devices exhibit versatile connectivity capabilities. They establish communication links not only with stationary objects but also with moving ones, such as AGVs even at speeds below 10 meters per second. This versatility makes them adaptable to a wide array of operational scenarios, ensuring effective communication and coordination.

Multiple Frequency Bands: To overcome environmental constraints, such as line of sight blockages, these devices are designed to support multiple frequency bands. This flexibility is essential in maintaining robust and uninterrupted communication, particularly in scenarios where obstructions might disrupt signals. Innovative solutions like reflective intelligent surfaces can further enhance coverage at high frequencies.

Energy Efficiency: These devices strike a balance between performance and sustainability by prioritizing energy efficiency. They are designed to minimize power usage, taking into account environmental concerns. This focus on energy efficiency not only ensures optimal performance but also reduces their overall environmental impact, aligning with broader sustainability goals.

Interoperability and Standardization: Efforts towards interoperability and standardization are central to this device class. They are designed to seamlessly integrate with other devices, networks, and systems. This harmonization extends to aspects such as network architecture, data formats, and device interfaces, ensuring that these devices can collaborate effectively in a variety of environments and ecosystems.

4.3.2 Other characteristics

Furthermore, there are various additional characteristics that might hold significant significance for the class of highly reliable low latency devices, depending on the specific demands of the given scenario. These characteristics encompass:

Accurate positioning: It is essential for optimal resource management, safety response, asset tracking, etc. For instance, in the specific use-case of cobots, maintaining precise positioning (1 – 5 cm) must be supported at a 10 to 10000 Hz refresh rate. Accurate positioning is one of the crucial KPI as discussed in one of the use-case on smart transportation vehicles in [HEX23-D14] of achieving 1mm to 1cm every 20 ms. This precision is crucial not only for cobots but also for other devices such as AGVs, where real-time accurate positioning enhances navigation and coordination within industrial environments, ensuring efficient and safe operations.

Time synchronization: It is crucial based on factors such as the specific use-case's network infrastructure, constraints related to latency, and the required levels of synchronization accuracy and precision to ensure seamless coordination and efficient data exchange.

3D positioning: It majorly holds significance in applications such as inventory management, enabling accurate tracking of items within a three-dimensional space. This capability enhances inventory accuracy, streamlines logistics, and optimizes resource allocation for improved operational efficiency. For instance, in devices like cobots and AGVs, where high reliability and low latency are paramount, 3D positioning plays a crucial role. These devices require precise spatial awareness to collaboratively navigate and interact with their surroundings. The combination of high reliability ensures consistent and error-free positioning, while low latency guarantees swift and real-time responsiveness, making them highly effective in dynamic and collaborative environments.

Local computation: It encompasses on-device tasks such as data analysis, filtering, and inference, allowing devices to process information independently. This capability enhances efficiency by reducing the need for constant data transmission and central processing.

Security and privacy: It is an essential safeguard for these devices to majorly ensure confidentiality and unauthorized access.

Use-case specific: Example use-case, cobot’s environment mapping and object sensing with a range resolution <0.01 m and velocity resolution 0.1 m/s [6GB21-D21].

Other Features: This includes aspects like establishing safe axis range, detecting collisions, task scheduling and assignment, etc.

4.3.3 Technology enablers

Key technology components will support the advancement of highly reliable, low latency devices, as discussed earlier. Among the various characteristics mentioned, this elaboration delves into the most promising enabler anticipated to uplift these devices as following:

- Use of 6G spectrum for accurately sensing the space along with communication capabilities. By integrating radio-based sensing with cutting-edge sensor technologies such as LiDAR and 3D imaging, they enable devices to create detailed and reliable maps of their environment while avoiding obstacles. This integration promises breakthroughs in spatial awareness, benefiting applications like autonomous vehicles and smart cities.
- Enhanced sensing with accurate perception and data collection, so as to enable devices to make informed decisions and respond effectively to changing conditions. Devices equipped with these advancements can perceive their surroundings with exceptional accuracy. As a result, they can make well-informed decisions and respond adeptly to dynamic conditions. This heightened operational intelligence has transformative potential across various industries, from healthcare to industrial

automation. In contexts where low latency and high reliability are paramount, such enhanced sensing capabilities enable devices to operate seamlessly, ensuring optimal performance in real-time applications.
- Natural Language Processing (NLP) serves as a technological enabler, particularly in applications spanning applications like cobots, AGVs, etc. NLP empowers these devices to understand and respond to human commands swiftly and accurately, contributing to low-latency communication. By interpreting natural language inputs and gestures, NLP facilitates seamless and intuitive interaction between devices, ensuring effective collaboration. This technology significantly reduces the latency in communication, aligning with the stringent requirements of high-reliability applications. In scenarios like manufacturing, where precision and quick response times are crucial, integrating NLP enhances the overall efficiency and adaptability of the device class, making it out as a crucial facilitator.
- Prioritize power saving techniques, secure communication, and effective energy management for reliability and safety. By optimizing energy consumption and implementing robust security measures, devices can maintain consistent performance while minimizing their environmental impact. Meticulous energy management further reinforces reliability, a crucial aspect for critical applications in fields like healthcare and transportation.

4.3.4 System/infra enablers

Edge computing

Enabling a highly reliable, low-latency device class necessitates a robust system and infrastructure, with a crucial focus on edge computing. These devices demand the capability to make split-second decisions while maintaining seamless connectivity and ensuring human safety. This involves equipping these devices with potent onboard processors, dedicated AI accelerators, and data pre-processing capabilities and then leveraging edge computing to complement this and significantly reduce latency, ensuring swift responses to real-time events. Additionally, edge computing enhances scalability, allowing the device class to adapt to varying workloads efficiently. While, onboard computing supports autonomous operation, enabling devices to execute tasks independently and adapt dynamically to their environment; the compute heavy tasks such as environment mapping can be done on the edge. It also ensures energy efficiency by optimizing the usage of computing resources, extending operational periods between recharges. Moreover, onboard computing enhances the device class's resilience, ensuring seamless operation even in environments with intermittent or limited network connectivity.

RIS

Another enabler that could support this class of devices is RIS. It could serve as an enabler, especially at higher frequencies (for e.g., sub-THz, mmW), to improve reliability and availability and enhance coverage. RIS may not be very relevant for <FR2 (as there are other alternatives such as multiple-input multiple-output (MIMO) to enhance coverage/ reliability).

4.3.5 Sustainability considerations

The sustainability considerations for this device class are grouped under the following three sustainability pillars:

Environmental sustainability:

- Optimizing power consumption is a critical strategy for environmental sustainability. By optimizing power consumption, devices can significantly reduce their energy needs, leading to cost savings and a smaller environmental footprint. This approach aims to balance effective operation with minimal environmental impact, reducing the need for maintenance and ensuring long-term sustainability.
- The maximization of renewable energy sources is essential for environmental sustainability. This involves integrating energy harvesting solutions into IIoT devices. These solutions, such as leveraging solar panels and wind turbines, enable devices to generate their energy, reducing their reliance on non-renewable sources. This shift towards clean and sustainable energy aligns with global environmental objectives, contributing to an eco-friendlier future.

Social sustainability:

- Ensuring consistent and dependable connectivity, data transmission, and system operation to support critical industrial processes and applications. This reliability is crucial for supporting critical industrial processes and applications, which, in turn prevents disruptions.
- Robust security measures are paramount for social sustainability. These measures protect workers, communities, and the integrity of data and systems. Prioritizing security fosters trust, upholds social responsibility, and ensures the well-being of those involved in industrial processes and applications.

Economic sustainability:

- Enabling seamless integration and communication among heterogeneous IIoT devices contributes to economic sustainability by promoting efficient data exchange, reducing operational inefficiencies, and fostering streamlined collaboration across the industrial landscape.

4.3.6 Key performance parameters

The following key performance parameters are expected from this device class in terms of:

Radio performance:

- Multi-hop capability is a crucial KPI that enhances network resilience. It enables data to hop between multiple nodes, overcoming obstacles and signal interference often present in complex industrial environments. This capability ensures that data can reliably reach its destination, even in challenging conditions, promoting the robustness and dependability of the network. Devices such as cobots and AGVs, operating in dynamic and challenging environments, rely on seamless communication. The ability to hop between nodes ensures that critical data, essential for real-time decision-making, can traverse the network with minimal latency, contributing to the overall reliability of these advanced devices.
- Coexistence with other networks and network scalability are essential radio performance KPI. They ensure the smooth operation of communication systems, especially in congested environments. Scalability allows the network to adapt to changing demands and grow seamlessly while coexistence prevents interference and conflicts with other nearby networks, supporting reliable and interference-free communication. The ability to coexist harmoniously with other networks ensures uninterrupted communication, crucial for real-time decision-making. Additionally, scalability becomes vital as these devices may be part of dynamic and expanding ecosystems, requiring the network to grow seamlessly. These KPIs are instrumental in maintaining the reliability and low-latency performance of devices operating in complex and network-dense industrial settings.

Energy consumption:

- Efficient power management encompasses strategies like standby mode implementation, monitoring of consumption across peak, idle, and active states, all of which collectively contribute to optimizing energy usage and enhancing device performance. Optimized energy usage ensures that these devices can operate consistently in various states, be it peak activity or standby mode, without compromising reliability or latency. As these devices are integral to real-time operations, their ability to efficiently manage power becomes paramount for sustaining performance, reliability, and low-latency responsiveness in dynamic industrial settings.

4.3.7 Link to use-cases

These devices find applicability across numerous defined use-cases, with the most pertinent ones comprising:

- Outdoor deployment in environments like construction sites and agricultural plantations. Devices are designed to withstand harsh conditions and provide data for applications such as precision agriculture and equipment monitoring.
- Indoor deployment scenarios encompass consumer homes and production/manufacturing environments. Devices are employed in smart home automation and industrial automation, ensuring efficient and safe operations.
- Warehouse inventory management utilizes devices such as unmanned aerial vehicles (UAVs) to facilitate rapid inventory tracking and management, improving logistics efficiency and reducing manual labour.

- Enhanced remote healthcare applications include remote health monitoring, telesurgery, and personalized healthcare solutions. These technologies bring medical expertise to remote locations and enable tailored medical treatments.
- Predictive maintenance use-cases focus on monitoring and optimizing machinery and infrastructure. This approach prevents breakdowns, enhances safety, and improves overall system efficiency through data-driven insights.

4.3.8 Example devices

Highly reliable and low latency devices encompass a broad range, and some example devices, for cobots and IIoT use-case, are outlined as follows:

- Cobots use-case: These devices encompass a wide array of devices designed for human-robot cooperation. Telesurgery systems enable surgeons to perform precise surgeries remotely, expanding access to medical expertise. Robotic arms are integral in manufacturing, assisting with tasks like assembly and welding. Mobile cobots autonomously navigate various environments, finding applications in warehouses, hospitals, and factories. Exoskeletons aid individuals with mobility limitations, enhancing their independence and mobility. AGVs optimize logistics by automating material transport, while grippers and manipulators are crucial in industries requiring intricate object manipulation, such as manufacturing and packaging.
- IIoT use-case: These devices include diverse range of devices that revolutionize industrial processes. Asset tracking devices monitor the location and condition of valuable resources, bolstering supply chain efficiency and security. Wearables, like smart helmets and wristbands, equip workers with real-time data for enhanced safety and productivity across various industries. Smart sensors are strategically deployed in industrial settings to collect data on machinery performance, environmental conditions, and more. This data enables predictive maintenance and process optimization, driving efficiency and sustainability in industrial operations. The IIoT plays a pivotal role in modernizing traditional industries by infusing them with connectivity and intelligent data-driven insights.

4.4 Enhancements of mMTC device class.

The term machine type communication (MTC), or machine-to-machine (M2M), describes communication between various types of devices or machines with minimal human interaction and is a key concept within the realm of IoT, where numerous such terminals are interconnected over the Internet to enable seamless communication. In that sense, massive MTC (mMTC) refers to the challenges and requirements for providing a service interconnecting a vast number of such devices in a network.

Cellular technology specifications and enhancements from 3GPP to support MTC/mMTC, and the resulting IoT applications, have a rich recent history of development [ING21-D31]. In Release 13 (2016), the Extended Coverage Global System for Mobile communications in the context of IoT (EC-GSM-IoT), based on enhanced general packet radio services (eGPRS), was introduced as a Low Power Wide Area (LPWA) technology to address M2M applications. The general target was to introduce devices of longer range and battery life compared to 2G devices based on regular GSM/GPRS and of lower cost and complexity to 3G devices based on High-Speed Packet Access (HSPA), that could also be used for MTC [LSW+17]. However, EC-GSM-IoT has never really been deployed and 2G MTC devices still operate in practice using regular GSM-based technology. At a parallel timeframe (i.e., Release 13), 3GPP released two technology variants based on the 4G-oriented air interface Long-Term Evolution (LTE) targeting LPWA use cases and IoT applications: LTE-M, also known as enhanced MTC (eMTC), and narrowband IoT (NB-IoT). These two technologies made possible, and largely competitive for IoT, the existence of 4G MTC devices. NB-IoT is designed to operate in very small 180 kHz channels and with high inherent transmissions redundancy, allowing very flexible deployment over the spectrum and device solutions better fitting low data rate, low mobility, and high coverage IoT applications. On the other hand, eMTC is designed to operate in regular LTE deployments, using the smallest possible channel size of 1.4 MHz, allowing device solutions with seamless LTE implementation and richer capability to support more demanding IoT applications, including voice over LTE (VoLTE). The devices supporting LTE-M and NB-IoT technologies are commonly termed as Cat-M and Cat-NB, respectively, while each device category has two variants, Cat-M1/M2 and Cat-NB1/NB2, where second variant generally denotes a device of higher throughput capability. Cat-M and Cat-NB can be seen as reduced capability versions of regular LTE devices, with their primary design objectives being:

- **Reduced cost, smaller footprint:** Only one device antenna is possible in LTE-M and NB-IoT designs, simplifying signal processing, compared to the regular LTE using two antennas on the device side. Additionally, use of smaller channel sizes further simplifies processing. Finally, LTE-M and NB-IoT real deployments mostly operate under half-duplex frequency division duplex (HD-FDD), the mode which allows the UE to transmit and receive data on different frequencies, but not at the same time. With HD-FDD, there is no need for a duplexer (the specific filter that protects the receive path from the transmit signal), allowing a drastic simplification of the radio front-end and a single hardware design to operate globally.
- **Improved coverage:** Removing one antenna negatively impacts receiver sensitivity, so in order to compensate for this loss and to improve the coverage (as necessary for deep indoor deployments such as smart meters), coverage enhancement (CE) modes are introduced. CE modes (i.e., CE mode A optimized for moderate coverage enhancement and CE mode B providing extremely deep coverage) are simply signal repetitions, and although not an optimal solution from an information theory standpoint, they are a low-cost technique for improving signal-to-interference-plus-noise ratio (SINR).
- **Very long battery life:** New power saving schemes, namely, extended Discontinuous Reception (eDRX) and Power Saving Mode (PSM), and protocol optimizations were introduced allowing devices to enter into a deep sleep mode as fast as possible and as long as possible, resulting in a reduction of power consumption to the lowest level possible.

Both LTE-M and NB-IoT technologies and respective devices are now deployed extensively all over the world while they have been keep evolving and improving in subsequent 3GPP releases. In fact, after enhancements in Release 14 (2017) and Release 15 (2019), the two technologies were accepted by ITU for meeting the minimum requirements for the 5G mMTC usage scenario of IMT-2020 [M.2410-0]. Additionally, in Release 16 (2020), further enhancements included efficient coexistence with the 5G-oriented air interface New Radio (NR) and support of connection to 5G core (5GC) network, Release 17 (2022) introduced more enhancements to support devices long-term lifecycle, address lessons drawn from deployments and trials, and broaden use cases for legacy cellular IoT, while the ongoing Release 18 is working on enhancing NB-IoT and LTE-M to address IoT operation in remote areas utilizing satellite connectivity.

In Release 17, 3GPP also specified a solution for reduced capability version of legacy (Release 15/16) NR devices, called Reduced Capability (RedCap) device. NR RedCap work targeted to enable devices of lower cost (around half of legacy NR devices), with relaxed capabilities such as reduced max channel bandwidth (e.g., 20 MHz for FR1, similar to regular LTE), single Rx antenna and single MIMO layer support. NR RedCap devices are targeting higher end broadband IoT use cases such as industrial wireless sensors, surveillance cameras, and wearables, with higher throughput or lower end-to-end latency requirements that cannot adequately addressed so far by Cat-M and Cat-NB (i.e., equivalent to capabilities of regular Cat-1 or Cat-4 LTE devices). Additionally, in Release 18 ongoing specification, an enhanced reduced capability (eRedCap) device variant is being designed, with main feature the support of 10 Mbps data rate, either through bandwidth or peak data rate reduction (i.e., equivalent to the LTE Cat1-bis solution, the LTE Cat1 version with only 1 Rx antenna, whereas Rel.17 RedCap can support around an order of magnitude higher rate). This eRedCap device variant targets to cover the capability and cost gap between RedCap and LTE-based solutions but still seems to be more fitting towards the lower-end broadband IoT applications.

In 6G era, device solutions for mMTC will need to become more competitive in terms of cost and power consumption while retaining or even advancing their capabilities to efficiently enable use cases requiring massive IoT connectivity and experience such as e-health for all, immersive smart cities, or hyperconnected networks for manufacturing, in a sustainable manner as well. Looking at 5G, RedCap/eRedcap are not direct replacements for LTE IoT (Cat-M, Cat-NB), with much higher delta in performance capability and cost. Even LTE IoT devices for LPWA networks are more expensive than non-cellular solutions (LoRa/SigFox/Wi-SUN/etc.) and most IoT devices deployed today are not cellular, despite the significant advantages of cellular deployments (e.g., reliable and predictable performance, future-proof and long-term support, reuse of existing infrastructure for new services). Tougher specs, extensive certification and interoperability testing, bigger batteries, wider antennas, are some of the factors contributing to that situation. 6G needs to answer these challenges and bring to life enhanced, low-cost and low-impact solutions for future mMTC scenarios.

4.4.1 Key characteristics

The enhancements of cellular IoT technologies for mMTC are envisioned to continue, either via the Cat-M/Cat-NB route, or the RedCap route (e.g., by introducing a further enhanced RedCap variant), resulting into enhanced 6G-compliant mMTC type devices. These enhancements are expected mainly to continue improving on the device cost and energy conservation, enable slightly higher data rates (up to few Mbps), 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 MTC devices. As shown in Figure 4-5, the evolution of cellular IoT for mMTC devices is expected to lie, in terms of capabilities, cost and energy consumption, between the 4G/5G solutions for broadband and/or critical IoT and the various envisioned solutions for Ambient IoT.

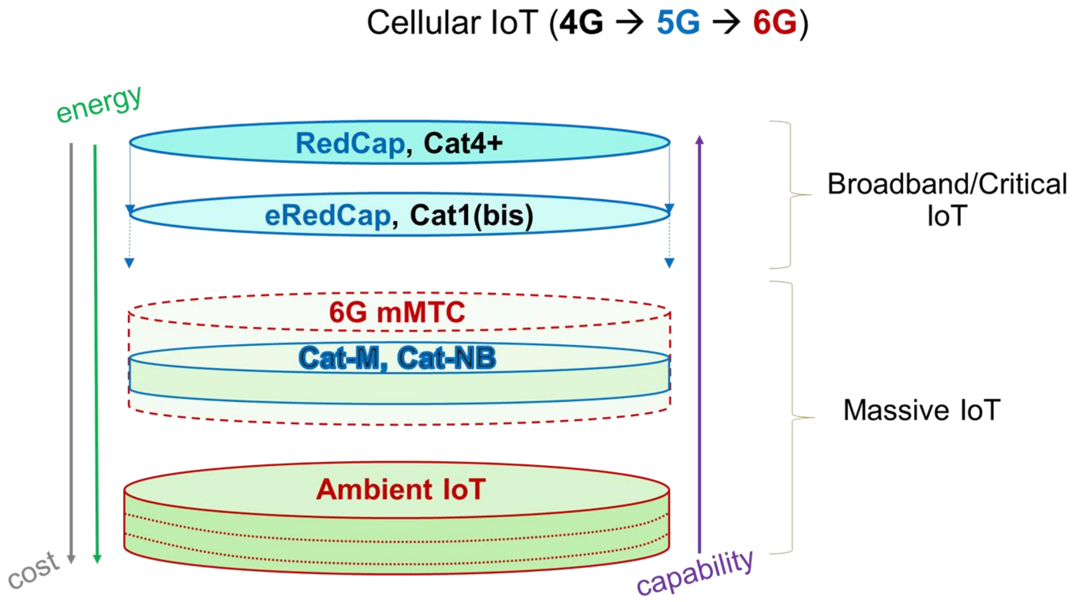

Figure 4-5: Evolution of cellular IoT and respective devices from 4G to 6G

The key characteristics of this device class include:

- **Low device complexity and cost**: A reasonably low device complexity and cost (e.g., up to ~1/3 of broadband/critical IoT devices) is essential to enable widespread and massive adoption. Low complexity and cost can be supported by several strategies such as simplified hardware, e.g., including small number of antennas and RF chains, efficient connectivity options that balance cost and performance, such as usage of narrow bandwidth, cost-effective materials and simple manufacturing processes, minimal user interfaces, testing and conformance needs, etc.
- **Small data volumes**: mMTC devices are ideal for applications where low data volumes are sufficient. Usually, these applications also involve infrequent and asymmetric (potentially UL-heavy) traffic, which can be either periodic or event-triggered sparse reporting, and communication can be optimized for low data rates involving data aggregation.
- **Enhanced coverage**: The aim is to not only support short range communications of a few meters, but also communication scenarios of enhanced coverage. This is crucial for ensuring devices' reliable connectivity in various applications, especially considering network cases where a large number of terminals is spread over a wide area (e.g., in urban areas of several km^2), or rural areas of ranges over 10 km and deep underground cases where signal conditions are very poor, requiring signal amplification techniques and several levels of redundancy or signal repetition. It should be noted that high coverage requirements commonly entail the use of sub-6 GHz spectrum (FR1).
- **Long lifetime**: This is a common essential requirement of mMTC devices to ensure their deployment sustainability for several years (e.g., up to 10-15 years under extreme coverage), reduce the operational costs and minimize maintenance efforts. Especially considering scenarios relying solely on battery,

mMTC devices must depend on efficient power management techniques, optimized data transmission to communicate only when necessary, and advanced battery technologies of low self-discharge.

- **Fixed to high mobility**: mMTC devices are useful in scenarios where terminals are located in specific areas, fixed in place, but also in scenario of high mobility, e.g., up to 120 km/h, but potentially also above those speeds considering low-earth orbit (LEO) satellite or high-speed train communication for example. In first case, communication protocols can be optimized for reliable communication and performance efficiency, while in second case, efficient handover management and tracking capabilities (among others) become of paramount importance.

4.4.2 Other characteristics

There are also several other characteristics which, depending on the scenario requirements, can be also of critical importance for the mMTC device class. These characteristics include:

- **Potentially small form factor**: mMTC devices are commonly deployed in scenarios where size is critical factor, leading to solutions employing miniaturized components such as microcontrollers and miniaturized antennas, integrated circuits and system-on-chip (SoC) design combining multiple functions into a single chip, compact and lightweight materials for enclosures and packaging, etc.
- **Limited battery capacity/size**: mMTC devices usually come with the constraint of limited battery capacity and/or size (due to needs for small form factor or even environmental conditions and regulatory compliance, such as the case of goods tracking on shipping applications), while having to achieve long lifetime targets, as already mentioned. Several options can be applicable according to scenario needs and constraints, such as non-rechargeable lithium batteries with consistent voltage output for infrequent data transmissions and potentially hard-to-reach-for-maintenance scenarios, AA/AAA batteries for moderate power demands and less critical size constraints, or coin cell batteries for more compact devices with lower energy capacity and density requirements.
- **Expectation of long duration wearability**: Durable and long wearability mMTC devices are commonly required, linked closely to the needs of low maintenance needs, high power efficiency but also for user experience and comfort, for example in case of eHealth IoT applications. Apart from battery and form factor optimization, the durability characteristic may entail flexible, soft, lightweight materials and durable (to withstand daily wear and tear), waterproof, or even ergonomic design.
- **Large connection density**: as the device class name indicates, mMTC refers commonly to scenarios where a vast number of terminals is communicating, essentially leading to large density of connections to the network. This poses special challenges to the network architecture and the design of access schemes to ensure efficient use of resources and minimizing collisions of transmissions. From device point of view, it may entail need to support very dynamic connectivity as well as mechanisms improving signal quality and resource efficiency such as massive MIMO, beamforming and groupcast communication.
- **Relaxed latency and availability**: It is also quite common characteristic for mMTC to have relaxed latency and/or availability requirements, such as in the case of periodic meter reading or environmental monitoring in smart city scenario. This allows for trade-offs that can enhance performance and energy efficiency, such as low-power aggressive duty and sleep cycling, or reduce complexity and cost, e.g., through looser data rates, synchronization or handover needs.
- **Potentially high accuracy positioning/sensing**: This can be also a critical characteristic for several applications involving for example asset tracking, location-based services, or logistics. Such high-level accuracy positioning may have to rely on techniques based on GNSS systems, network-based positioning such as Cell-ID, Time-of-Arrival (ToA) measurements, positioning reference signals, etc., combination of aforementioned techniques, or even AI/ML algorithms (possibly with computational complexity offloaded to the network) for improving accuracy prediction. It is also possible that future mMTC devices will need to include accurate sensing for real-time understanding of the environment in general as a feature, jointly with communication, using shared circuitry and blocks for proving both capabilities in an efficient way.
- **Secure device and communication**: Finally, ensuring security of mMTC devices can be crucial to several IoT services which will have the need to provide data privacy, prevent unauthorized access, and maintain the integrity of communications. Security aspects can regard device firmware/software

and hardware to prevent data manipulation, connectivity to network for identity privacy, secure information exchange and ensured access integrity, as well as application and service for end-to-end data communication security. To enable such secure and trustworthy devices and communication, several strategies are possible, which however have to be designed efficiently considering the several constraints (low complexity/power, etc.) of this device class: strong authentication mechanisms for only authorized devices accessing the network, end-to-end encryption for protected data communication between device and network (including e.g. transport layer security (TLS) for secure communication over the internet and message queuing telemetry transport (MQTT) with TLS for secure messaging), secure boot and firmware updates, protected environment for encryption of data stored and processing of sensitive data on device (via, e.g., a secure element hardware component), isolated secure components with trusted transfers on Network-on-Chip (NoC), etc.

4.4.3 Technology enablers

Several technology enablers will drive the enhancement of mMTC device class. Numerous solutions and enablers for realising mMTC devices have been already mentioned in the discussion above regarding the devices class key characteristics. Here, we expand more on the most promising ones envisioned for the near future enhancement of mMTC devices:

- **Power saving techniques and design**: with mMTC device battery lifetime a key characteristic, mechanisms for pushing device power efficiency to the limits are of paramount importance. One aspect affecting energy efficiency of the device has to do with low consumption when there is no data. Adaptive go-to-sleep (e.g., micro or deep sleep modes) and wake-up (potentially triggered) mechanisms and dynamic transitions can make excellently efficient use of sparse and bursty data traffic involved in most scenarios relevant to mMTC. Another aspect important to device energy efficiency is the minimised consumption for transmission during network access (i.e., when data communication is involved) or for measurements dedicated to radio resource management. For those phases, power saving mechanisms can focus on limiting the factors of dominant consumption, such as active Tx/Rx time, activity time of RF chain(s), synchronization time/effort in bad channel conditions, adaptive time on measurements according to device conditions (e.g., mobility level), etc. Finally, the design of the device around the triggering and reception of sparsely required communications (leading to frequently available low power modes) is also a crucial aspect for its energy efficiency. For example, a low-complexity low-power wake-up signal and device wake-up receiver design could bring significant power savings since the highly consuming main radio hardware module will not have to be active when not really needed [38.869].
- **Cost effective design and operation**: the mindset towards design of enhanced mMTC shall stay focused on the path of low-cost end solutions. There are several traditional ways to reach the desired price/performance cut-off points and new trade-offs shall be investigated to optimize network capacity, coverage and desired user experience. These include for example 1) low number of antennas (eventually Tx/Rx paths) together with appropriate advanced techniques, e.g., codebook-based precoding, for alleviating coverage impact; 2) narrower channel bandwidth designs (e.g., 5 MHz down to sub-MHz) to address more efficiently the easily achievable very low throughputs (few 100s of kbps) required in several IoT applications; 3) Half duplex FDD (HD-FDD) as a native 6G air interface duplexing option, which considers the split of channel bandwidth in two bands for either receive or transmit at a given time, leading to alleviated requirement of special integrated filter at RF front-end for isolated Tx/Rx path, and eventually dramatically reduced device cost.
- **Coverage enhancement techniques**: Given the degradation resulting from needed approaches to reduce device cost and complexity, such as the loss of diversity from use of a single antenna or the antenna gain loss from small form factor for example, it will be necessary to introduce techniques for coverage recovery. Furthermore, based on specific use case requirements, mMTC type devices may need to be more readily available of relatively frequently communicating for a time period. In that case, advanced techniques for deep synchronization can prove useful in order for the device to stay connected to the network (still at low power / sleep state), instead of being required to perform frequent costly re-attachments. Finally, supporting slightly high data rates of few Mbps may require sacrifices on redundancy of channel/signal transmission which in turn will require additional coverage recovery

techniques based in time, frequency, or power domain, without compromising the device's overall energy usage targets.

- **Coexistence with 6G air interface and core network**: Similarly, to LTE-M and NB-IoT evolutions for efficient coexistence with NR and support of connection to 5GC, the enhanced mMTC devices should have ensured coexistence with 6G air interface and support of 6G core network. In case of using legacy cellular IoT technologies, 6G air interface could be designed ab initio to support dynamic spectrum sharing (as was the case with NR), while enhancements may need to be provisioned in order to accommodate peculiarities of legacy technologies and device behaviour, e.g., always-on legacy signals. Additionally, support of connection to 6G core network should also include support of the various legacy radio resource control (RRC) modes and procedures, e.g., RRC idle/inactive, extended DRX, etc.

4.4.4 System/infra enablers

mMTC type devices will need to be connected everywhere and anywhere, and certain cases will require a very large connection density. The necessary infrastructure and system design must be in place in order to provide the required connectivity and backend support for feasible functioning of IoT applications based on mMTC devices. The main infrastructure enablers envisioned include:

- Ubiquitous low-power wide-area network deployment (base stations, gateways, management platforms) to support IoT applications suitable for mMTC devices requiring, e.g., close to 100% network availability or worldwide coverage, remote management of devices for configuration/monitoring at scale.
- Network capability to support concurrently a large device connection density, with capacity for scalability, load balancing and resource orchestration, while also maintaining the per device necessary communication performance requirements (e.g., high redundancy, availability and reliability, accurate and timely location services, etc.).
- Cloud and edge computing platforms to support potential needs of data storage, processing and analysis offloaded from mMTC devices.
- Efficient integration of connectivity technology with network architecture and novel systems for mMTC services billing and subscription management. Such enabler seems crucial for targeting a device subscription cost of similar order of magnitude to the actual device cost and realising massive deployments in practice.

4.4.5 Sustainability considerations

The sustainability considerations for the enhancement of mMTC device class are grouped under the following three sustainability pillars:

- **Environmental sustainability:**
  - Low energy consumption and demand throughout the entire device life cycle, from manufacturing, to operation, to disposal.
  - Low resource and energy usage impact per device to the network.
- **Social sustainability:**
  - Promote digital inclusion via ubiquitous and on-demand coverage (even for high connection density)
  - Promote well-being as well as digital inclusion by providing low-cost wearable and sensor services.
  - Promote social well-being, equity and security by providing for low-cost and ubiquitous emergency services for high connection density and preserving data privacy.
- **Economic sustainability:**
  - Low-cost device solutions that can be deployed in mass scale.
  - Low resource and energy usage impact per device to the network.

4.4.6 Key performance parameters

In terms of radio performance, the following key targets are expected from mMTC type devices considering that they are targeting LPWA use cases and low-end massive IoT applications [May19]:

- Connection density: up to 1 device per m2
- Coverage: up to 164 dB maximum coupling loss (MCL), at 160 bps data rate
- E2E latency: few (10-15) ms to few (≤10) sec
- Service availability: ≥99%
- Data rate: from 10s kbps to few (<10) Mbps

Considering that mMTC type devices will mainly refer to battery-based operation, energy consumption targets (considering the modem part of the device) should be supporting the use of relatively small size batteries for lifetime of several years, and should be similar to (or lower than) the power consumption of existing 4G/5G MTC solutions in the market:

- Dormant state: ~1 µA
- Reachable state: few 10s µA
- Idle state: few mA
- Active state: few 100s mA

4.4.7 Link to use-cases

mMTC type devices are relevant to several use cases defined in [HEX223-D11] The most prominent ones include:

- E-Health for All: Small, lightweight, low cost, and low maintenance mMTC devices and sensors, enabling for example on-body monitoring and basic e-health services that can be delivered anywhere, will enable accessible and remote healthcare.
- Immersive Smart City: Resilient, low power/size/cost/maintenance mMTC devices and sensors for IoT, capable of coexisting under extremely high connectivity density numbers and in challenging coverage and interference environments, will enable management and risk prevention of city infrastructure through digital twinning.
- Small Coverage, Low Power Micro-network in Networks for Production and Manufacturing: Large populations of sensors mounted in manufacturers' machines and vehicles, mutually connected (possibly in a very trustworthy way) with very low-power, low-cost, small form factor and resilient mMTC devices, will enable energy and spectrum efficient production and manufacturing.

4.4.8 Example devices

mMTC type devices include a large spectrum of terminals, ranging from sensors, meters and trackers to low-cost wearables and smart devices. Figure 4-6 summarizes some example devices in current market that lie within this mMTC type spectrum.

Figure 4-6: Example mMTC type devices

5 Conclusion and Outlook

Analyzing the use-cases in Hexa-X project such as [HEX21-D12], [HEX22-D13] and [HEX23-D14] along with the ones in Hexa-X-II [HEX223-D11], three distinct device classes that would be novel (compared to 5G device types) in 6G time frame were identified and a fourth one related to enhancement of existing 5G device type is also envisioned.

Furthermore, from use-case and services trends that could manifest in 6G time frame, we could see possibilities for the following as future work:

- **Potential new device classes:**
    - **Enhancements of eMBB devices:**

      This type of devices will primarily be about extending the data rates beyond 5G rates and making use of centimetric and sub-THz frequency bands in addition to frequencies supported in 5G. They will not have any mandatory requirements on latency, reliability, or availability. It is anticipated that one of the critical technology components that will enable this type of devices is that sub-THz frequency bands in addition to other frequencies such as mmW. Therefore, the current thoughts on the design methodology and scenario parameters related to sub-THz transceiver design is presented in Appendix A.
    - **Enhancements of URLLC devices:**

      Some literature, such as [ADS+22] points to insufficiency of current (5G) URLLC services that address 1ms latency at reliability of $1\text{-}10^{-5}$ (five 9s) for future services. This could motivate the need for enhancements of URLLC with lower than 1ms latency and higher than five 9s reliability along with higher data rates and massive connectivity. These challenging combinations are being motivated for the similar use-cases (or their extensions) cited in Section 2.1 and therefore motivate a through approach to understand first the deltas in the use-cases and do a deeper analysis of the requirements. Hence this could be a potential device class by itself or an evolution of 5G URLLC device class.
- **Potentially novel device: Companion device:**
  Analyzing CaaS and mainly to enable CaaS at extreme edge, there is a need for advanced & secure compute for low capability/resource constrained devices such as low-cost sensors. These additional computing needs could be served by another device, which acts as a companion to these resource constrained devices. Further investigations in conjunction with 6G use-cases details, new requirements (if any), system design is needed to conclude if it will be an independent device class. This is another candidate for future work while the current thoughts are presented in Appendix B.
- **JCAS and device classes:**
  Joint communication and sensing (JCAS), wherein a wireless communication system is used to also provide the sensing capabilities, is seen as feature that finds application across different device classes and based on specific use-cases/scenarios. For example, in XR applications, it could be used to get a (near) real-time understanding of the environment that a user is traversing or in industrial scenarios where robots can detect a human nearby and activate safety features. The scenarios would determine the different parameters such as suitable spectrum (e.g., in sub-THz for higher resolution sensing), reference signal design, etc. in addition implementation choices such as shared signal processing blocks, special circuitry for Tx-to-RX cancellation etc. Thus, though there will be trade-offs based on the communication and sensing requirements, it is not seen as a separate device class, but rather a multi-mode device which could end up a sub-class with a device class.

The Hexa-X-II use-cases work will continue as indicated in [HEX223-D11] analyzing further use-cases, with possibly understanding deltas with respect to 5G scenarios, understanding technologies that are needed etc. Thus, it is possible that some refinements of the device classes identified in this document and the potential new device classes could be continued in upcoming deliverables and along with analyzing the sensing aspects further.

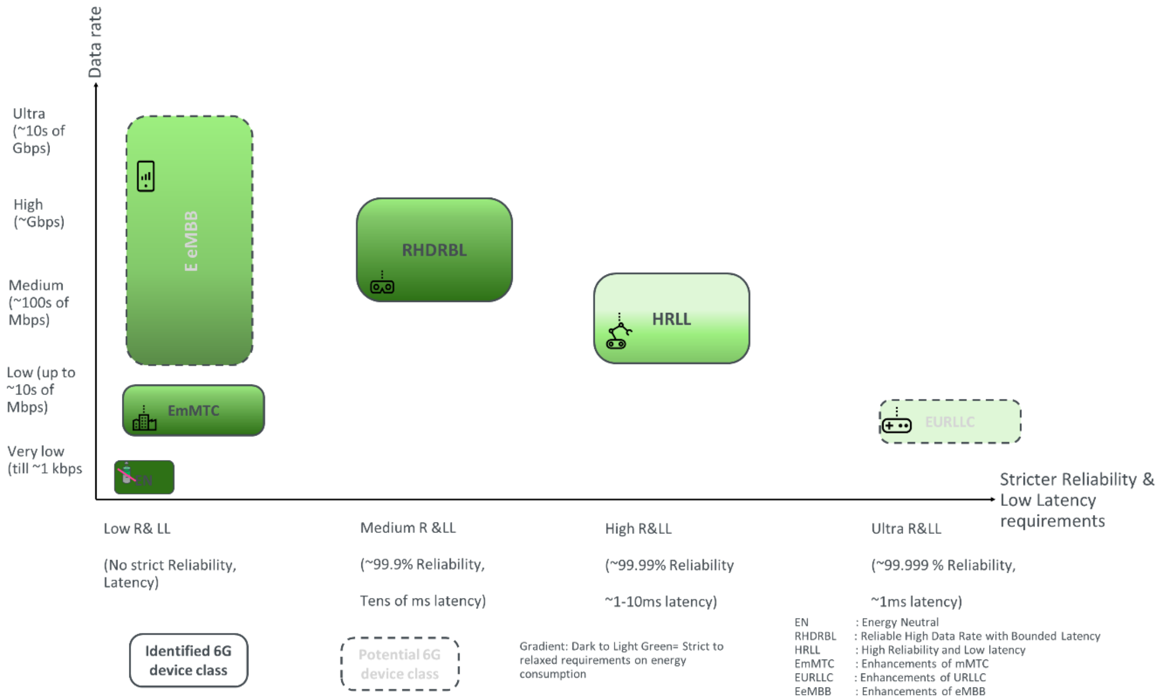

Figure 5-1: Summary of 6G device classes

The above Figure 5-1 depicts the summary of device classes. It is good to note that the solid boxes indicate the identified 6G device classes, while dashed boxes depict the potential 6G device classes. The green filling and its gradient depict the requirements on energy consumption, with dark green representing strict requirements on energy consumption Though availability requirements are not explicitly shown, it follows the same direction as the reliability ones for the device classes.

The following Table 5-1 contrasts the identified and plausible 6G device classes against the 5G ones.

Table 5-1: An overview: 5G device classes against 6G device classes

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 collaboration with humans. In the upcoming deliverables, this device class will be analyzed 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)	• EmMTC: improved cost and energy conservation, higher data rates while ensuring high coverage, possibly requirements on reliability, integrated

		- Enhancements of eMBB (EeMBB) - Enhancements of URLLC (EURLLC)	sensing capability, lightweight AI/ML techniques. - EeMBB: support higher data rates (and perhaps lower data rates than what is supported in 5G) but doesn't have any latency requirements. It could be utilizing new spectrum bands in 6G. - EURLLC: potentially new spectrum (for e.g., in cm), physical layer enhancements, optimization enabled by ML/AI etc. could be interesting.
Potentially novel from 5G	-	- Companion devices	These devices mainly augment lower capable devices with secure, advanced compute and connect them via flexible topology. They may have only limited possibilities for deployments. More details in Appendix B.

6 Appendix A: Sub-THz transceiver design

Sub-THz bands could be utilized to achieve higher data rates given the wide bandwidths available. To realize communication over sub-THz bands, a critical component is a sub-THz transceiver that is studied in Task 5.2. The corresponding dimensioning approach and link to scenarios are described in this section.

6.1 Design methodology

In order to design wireless systems, the following methodology is proposed and applied especially to sub-THz frequencies. Although the approach is relatively generic, the wider bandwidth and larger number of antennas associated to those frequencies bring specific design choices. A system is defined here as two or more transceivers communicating wirelessly with each other, and each transceiver contains the required components for physical layer (PHY) digital processing, analog front-end (FE) for baseband and RF, power amplifiers (PAs) generally considered separately from the rest of the FE, antennas with their interconnections, and device power supply.

At least two transceivers are considered, one acting as transmitter and the other as receiver. In many cases a bi-directional link is created between them, primarily assuming TDD and swapping their transmitter/receiver role. This section focuses primarily on the downlink (DL) direction between one infrastructure transceiver (typically part of a base station) and a user equipment transceiver, but the approach is generic and can also include communication between identical devices. When more than two devices are considered, we assume that the infrastructure transceiver is a central node connected simultaneously to multiple user transceiver and offering them several parallel links. We do not consider more complex topologies such as multi-hop scenarios or network routing aspects.

The objective is to dimension FE architectures and PAs (type of architecture, number of antennas, power levels, connections between components, semi-conductor technology, ...) and to specify the corresponding waveforms, signals and PHY digital processing algorithms. The main dimensioning and design steps are performed in the following order, with increasing complexity:

- Start from scenario specifications.
- Validate the target performance (mainly range and throughput) from link budget.
- Assess and optimize the power consumption and energy efficiency of transceiver architectures.
- Validate and optimize the physical layer algorithms under realistic conditions.

In the next section, we list and shortly explain the specifications required in order to clarify scenarios, in such a way that the different steps of the methodology can be performed with sufficient information. The design flow is tuned towards mm-wave and sub-THz communications (mainly 30 to 300 GHz) but can be extended to other bands, with possibly a reduced accuracy due to less dedicated models of component performance, power consumption, or propagation. The methodology also primarily assumes zero-IF (direct conversion) architectures.

The design flow mainly focuses on the in-band operation of the target system. Additional requirements may be included in order to also tackle interference aspects (from the target system towards other systems or vice versa). Based on the input scenario parameters specified in the next section, the proposed methodology determines the architecture offering the best solution by selecting and optimizing some of the following elements (not all of them are necessarily considered in each scenario):

- Type of architecture (analog, digital, hybrid, ...)
- Number of data streams, digital baseband streams, RF streams, PAs, antennas
- Type of analog phase shifting
- Specifications of DAC/ADC, phase noise, linearity, other non-idealities
- PA specifications (output power, efficiency, technology)
- Waveform, modulation and coding, frame structure for data and pilots
- Tx and Rx PHY DSP algorithms at BS and UE side

6.2 Scenario parameters

The relevant parameters to specify a scenario are listed in this section. For some of them, a unique value may be selected; for others, a range of possibilities or a list of requirements could be specified. Some parameters might come directly from the target application, while others could come from research interest, e.g., investigate a specific band or a specific category of architectures, or be specified by the system design.

Practically, application requirements that should be specified directly from the application scenario are listed in 6.2.1, as they quantify the desired performance of the communication solution provided. Other more specific technical parameters partially come out of the system design effort and related constraints, models and investigations. They are listed in sub-sections 6.2.2 to 6.2.4. Not all input parameters are mandatory for each architecture investigation. Depending on the type of optimization desired, some may be irrelevant or left to default values.

6.2.1 Application requirements

The end application requirements on the PHY connectivity should be expressed in parameters relevant to the wireless communication system design; some might be ignored in simple scenarios (such as single user):

- Geometry
  - Target range between both transceivers (minimum, maximum)
    - This may be generalized to include a distribution of users over the target range.
  - Angular spread of users as seen from the infrastructure transceiver
  - Minimal inter-user separation (in distance or angular)
- PHY performance
  - Target active (peak) throughput per user (DL, UL)
    - Possibly one minimal value and one desired (larger) value
  - Target BER (DL, UL)
- Mobility of the users (maximum speed or distribution)
- Number of simultaneously active users in the same band
- Maximum application latency (limiting power-down phases when duty-cycling between two packets)

6.2.2 Band of operation and regulations

In order to bound the design space, the main frequency and power parameters should be specified (they could reflect regulations, standards, or simple decisions on relevant scenarios):

- Carrier frequency
- RF bandwidth
- Maximum EIRP (Equivalent Isotropic Radiated Power) per stream
- Maximum total Tx power
- Possible waveforms, constellations, coding rate and options
- Maximum number of simultaneous users that can be spatially multiplexed.

6.2.3 Propagation channel

Wireless propagation is a complex domain with many different environments and related models. Besides geometrical parameters above related to range and angular domain, a minimal and relatively generic description is proposed here; additional parameters may be needed depending on specific use cases. Some are illustrated on Figure 6-1.

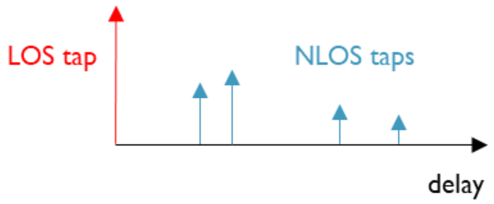

Figure 6-1: Tap-delay response where successive taps represent different propagation paths between the transmitter and the receiver, delayed based on the path length divided by the speed of light.

- Type of propagation: Line Of Sight (LOS) or Non Line Of Sight (NLOS)
- Delay domain statistics (see Figure 6-1)
    - Number of paths (the expected number of paths is the product of the density of paths by the maximum delay)
    - Density of paths (fraction of delay positions which are occupied by taps, at the channel sampling frequency which depends on the system bandwidth)
    - Maximum delay (corresponding to the last NLOS tap)
    - Tap amplitude distribution (the tap amplitude distributions are expected to lead a unit-energy normalized channel after integration of all taps over the delay dimension)
- Additional losses for NLOS paths as compared to LOS
    - This parameter can be the adjustment variable such that the tap-delay energy is normalized to one in expectation, i.e., it represents the large-scale fading as compared to LOS propagation while the tap amplitude distribution represents the small-scale fading; in the LOS case this parameter is trivially 0 dB
- Multi-antenna and multi-user correlations
    - Channel correlation between antennas of the infrastructure transceiver
        - Options range from fully correlated (where elements of the same antenna array share the same channel except for phase shifts related to their position and path angles) to uncorrelated channels over the different antennas (mainly for low-frequency or distributed systems)
    - Channel correlation between antennas of a user transceiver
        - The same model can be used at the user side if the antenna array is built with similar (antenna spacing) options.
    - Channel correlation between different users
        - For multi-user scenarios, the correlation or independence of channels over multiple user positions is an important parameter that needs to be specified
- Geometrical channel parameters
    - While the parameters above mainly refer to a statistical channel model combined with range and angles as specified in 6.2.1, another approach is to rely on a full geometrical channel model, e.g., using ray-tracing; in that case, other specific parameters are required to construct the channels:
        - Room/environment geometry and dimensions
        - Height and position of all transceivers
        - Elements creating reflections/diffraction/attenuation and related material properties

6.2.4 Transceiver architectures

Many parameters need to be selected or optimized in order to specify the design of transceiver architectures. This sub-section lists potential bounds or constraints that should be considered when selecting some parameters in order to obtain realistic architectures for the target scenario. It also includes specific sub-component performance limitations that cannot easily be modified and hence are used as inputs for the analysis. Those values may be different for infrastructure and user transceivers:

- Maximum consumed power
- Maximum number of antennas and array size
- Antenna element gain and interconnect loss.
    - Possibly antenna radiation diagram
- Noise figure
- Optimization criteria
    - Generally optimizing energy efficiency under performance constraints, but other options are possible.

7 Appendix B: Companion devices

In this Appendix, we outline a potentially a new device – companion device – that looks plausible in a 6G system and mainly acts as a node to augment computational needs of another device, especially resource-constrained ones and possibly utilizing short range energy efficient links. Thus, these companion devices are mainly helping to realize CaaS (described in Chapter 2.2.1), which is then more of a use-case enabling service. The Figure 7-1 below depicts the companion device and its connectivity.

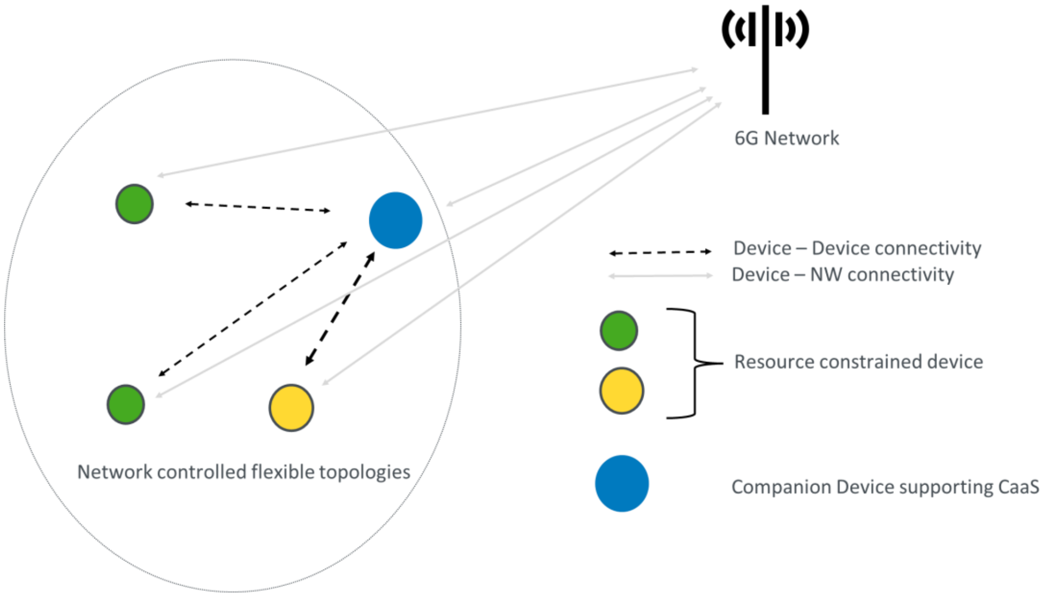

Figure 7-1: Companion devices and network controlled flexible topologies.

The companion devices are expected to interface with the served devices via a link under the control of the 6G system and accepts schedule from the 6G system. It should be able to simultaneously connect to both the Base station and its own served devices. The connections with served devices should be flexible, as in only if there is value in connecting, it should be set up. Thus, a flexible topology is needed among companion device and devices it serves, which can be set up by a 6G system that takes into consideration the authentication status, security requirements and resource capabilities of individual devices. Such flexible topologies also benefit from proximity detection of the companion devices and its potential served devices and is another feature that 6G system could provide. The availability and reliability of this topology could influence directly the QoS experienced by the end application. The connectivity (both between devices and between device & network) could utilize currently available spectrum and potential use the upcoming spectrum in centimetric range and sub-THz range. It is unlikely that sub-THz will be employed between device and network given the propagation path related constraints and connectivity will benefit from using licensed spectrum as interference could be reduced. It is to be noted that the flexible topologies with network control employed for CaaS could be one scenario that can be optimized for sub-THz transceivers (whose design aspects are covered in Appendix A).

The companion devices would be different from traditional gateways in that it has dedicated functions that helps a remote device with its offloading functionality. Some examples of these functions could be:

- Responds to mechanisms for discovery/detection of available compute resources (e.g., via a general register reachable by the CaaS provider).
- Interfaces with a functional entity (e.g., central controller/workload orchestrator) that decides when to offload (fully or partly) a processing workload.
- Ensures secure and trustworthy computation that doesn't interfere with services offered to other served devices. This security features should also include the system-on-chip interfaces and benefit from trustworthy network-on-chip interconnects that help securely connecting to shared computation units.

It is also plausible to have a device or a helper node, as in Chapter 4.1.4, which does only data buffering for devices in EN device class. It differs from companion device as it serves the EN devices with most likely a fixed, simpler connectivity and more specific authentication and security features.

Furthermore, unlike in the case of gateways, it is not necessary for the served devices to connect to the 6G system via the companion device but only when there is a need to augment its computational needs. For example, the low-cost sensors could receive data directly from the base station in a 6G system, but when this sensor needs some additional computation, it could connect to a trusted companion device to get energy savings.

The companion devices could influence the sustainability aspects. For example, it could influence the social sustainability by providing services that are cyber secure and respect end-users' privacy in addition to flexible and adjustable capacity and coverage. It could also influence economic sustainability aspects allowing low-cost/optimized devices to take advantage of additional features at shared cost.

In conclusion, though the companion device provides unique and novel features in 6G timeframe, it is currently not seen as an independent device class. This is because an existing device in a device class such as Reliable high data rate with bounded latency, could provide this feature additionally at a slightly more energy cost. While employing this computational offloading feature, it is not generating data by itself and as such it is not then really an end device in this operating mode.

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

The Joint Communication and Sensing (JCAS), also termed as Integrated Communication and Sensing (ICAS), is an expected 6G capability. In this Appendix, it is described how this key infrastructure enabler is associated with EN devices. An example scenario is depicted in Figure 8-1 wherein EN devices facilitates, for instance, to remove clutter or monitor known or partially known passive objects. Due to the characteristics of EN device, such as small form factor, low cost, energy efficient etc. it can be convenient to tag the clutter or object-of-interest with such devices. When the sensing is performed using JCAS~~,~~ then transmissions (active or backscattered) from EN device can further improve the accuracy. In the Figure 8-1 below, a passive object is identified using JCAS and EN based transmissions.

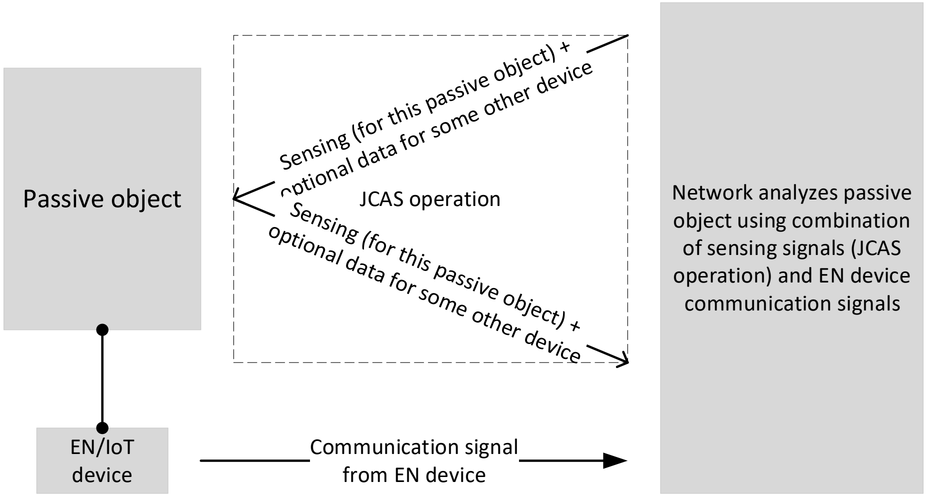

Figure 8-1: Network senses/detects a passive object using sensing signals and communication signals originating from a EN device which is linked to the passive object.

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