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GROUP REPORT

TeraHertz modeling (THz); Identification of use cases for THz communication systems

Disclaimer

Reference

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Foreword

This Group Report (GR) has been produced by ETSI Industry Specification Group (ISG) TeraHertz (THz).

Modal verbs terminology

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Executive summary

The present document identifies 19 use cases where THz communications play a major role. Besides technological benefits, described use cases equally bring societal benefits in various fields such as healthcare, education, entertainment, transportation, environmental awareness or public safety. Described use cases address various verticals and/or applications such as vehicular-related applications (V2X, railways, UAVs), XR, robotics, smart factories, smart homes, or ultra-high throughput delivery. The present document also identifies enabling technologies for THz communications, maps the identified use cases and deployment scenarios to relevant channel measurements scenarios, provides conclusions and formulates recommendations.

Introduction

With the large amount of bandwidth available in THz bands, it is possible to achieve extremely high data rates and ease spectrum scarcity problems. Moreover, specific propagation properties of THz signals unlock new features such as accurate sensing and imaging capabilities. The above properties of THz communications open the way to enabling new use cases and could provide an answer to new societal challenges that need to be addressed by the future 6G communications systems. Some of these challenges relate to new functionalities that are not currently supported by cellular systems (e.g. accurate sensing, mapping, and localization), while others relate to new use cases that were not supported by previous communications systems. The present document defines the new use cases that the THz communications and sensing systems can support, along with summarizing the requirements of those use cases.

1 Scope

The present document identifies and describes use cases either enabled by or highly benefiting from the use of THz communications. Aspects addressed in the present document include deployment scenarios, potential requirements, relevant operational environments and their associated propagation characteristics and/or measurements.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

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The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

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3 Definition of terms, symbols and abbreviations

3.1 Terms

Void.

3.2 Symbols

Void.

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AP	Access Point
AR	Augmented Reality
BER	Bit Error Rate
BS	Base Station
CoMP	Coordinated Multi-Point
CV	Computer Vision
D2D	Device to Device
DL	DownLink
ETCS	European Train Control System
HD	High-Definition
HiL	Hardware-in-the-Loop
HLS	High Layer Split
IoT	Internet of Things
ISAC	Integrated Sensing And Communications
KPI	Key Performance Indicator
LLS	Low Layer Split
LoS	Line of Sight
MIMO	Multiple Input Multiple Output
ML	Machine Learning
MR	Mixed Reality
NR	New Radio
NTN	Non-Terrestrial Networks
O2I	Outdoor-to-Indoor
OAM	Orbital Angular Moment
OOB	Out-Of-Band
ORAN	Open Radio Access Network
QoS	Quality of Service
RAN	Radio Access Network

RAT	Radio Access Technology
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
SDG	Sustainable Development Goals
SDN	Software Defined Networks
SLAM	Simultaneous Localization And Mapping
T2I	Train-to-Infrastructure
T2T	Train-to-Train
TCC	Train Control Centre
THz	TeraHertz
T-RIS	Transmissive Reconfigurable Intelligent Surface
UAV	Unmanned Air Vehicle
UE	User Equipment
UL	UpLink
URLLC	Ultra Reliable Low Latency Communications
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-everything
VR	Virtual Reality
XR	eXtended Reality

4 Use cases for THz communication systems

4.1 Use case on remote surgery

4.1.1 Description

The concept of remote surgery with support of THz communications comes with the promise of allowing people to be treated at anytime and anywhere, so that medical interventions could be done through the use of medical robots remotely controlled by a surgeon (away from the physical location where the actual surgery is performed). Other supporting technologies may be included such as Augmented Reality (AR) and/or haptic gloves. Such an example is depicted in figure 1. The requirements for such type of applications are very strict [i.1], [i.2]. The role of THz communications will become essential in such scenarios. On one hand, the use of THz technologies on the remote site extends human sensory capacities through the use of imaging, spectroscopy and high-sensitivity temperature detection, which are well recognized. On the other hand, real-time high-resolution video streaming in THz bands with KPIs as in table 1 is possible at remote and/or controlled sites, at a quality level not delivered by current systems.

The main social benefit of this use case is the accessibility to medical procedures/interventions in remote areas, in which there is a lack of specialized medical personnel. Moreover, robots could help to reduce the risk of contamination of medical personnel during the interventions [i.3] and improving the quality of healthcare.

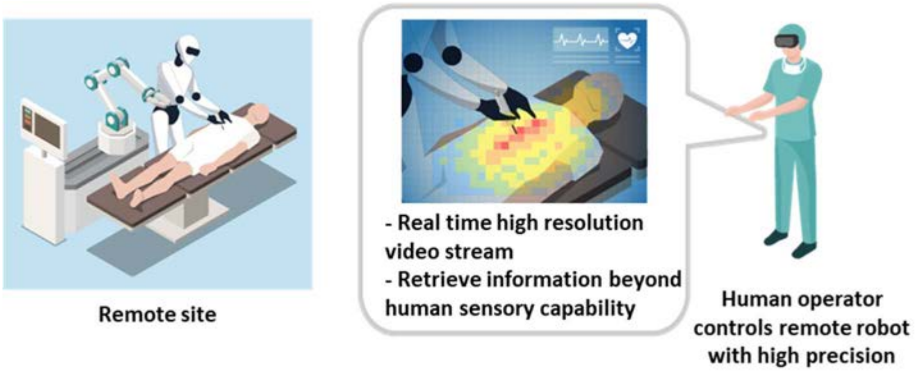

Figure 1: An example of remote surgery

4.1.2 Pre-conditions

Operating robots are equipped with sensing and communication capabilities. The human operator (e.g. surgeon) control equipment, the operating robot and all other involved equipment at the healthcare facility (e.g. sensors, possibly the passive side cart) have access to a THz access point. The remote and controller sites are in the coverage of a network operator providing connectivity with guaranteed latency and throughput.

4.1.3 Service Flows

- At the remote healthcare facility, the remotely controlled robot collects sensing information beyond human capability and high-resolution video stream of the surgical area.
- Sensory data is processed and transferred via a network that guarantees very high throughput and very low latency.
- At the controller site, the human operator (e.g. surgeon) is equipped with sensing reproduction devices and can also visualize high-resolution video stream of the surgical area.
- The human operator controls the remote robot via closed-loop feedback.

An example of service flow for remote surgery is depicted in figure 2.

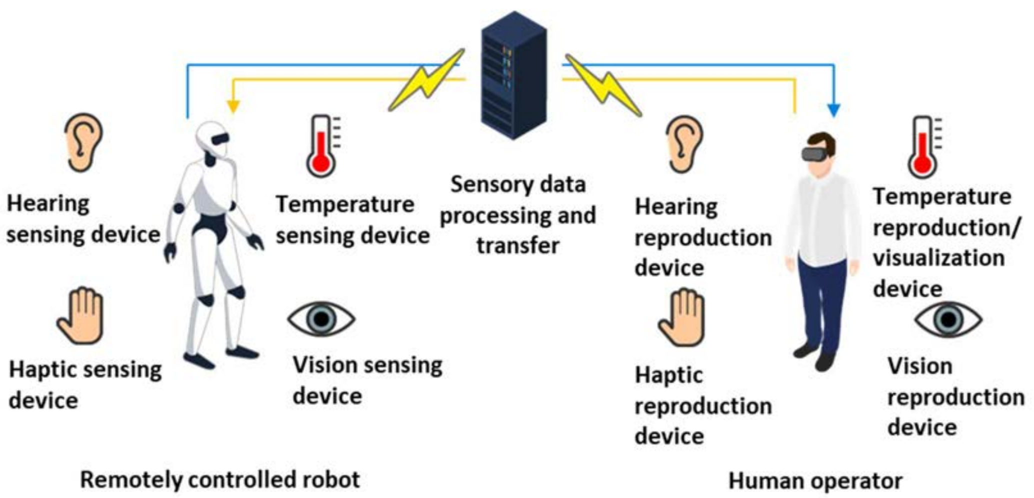

Figure 2: An example of service flow for remote surgery

4.1.4 Post-conditions

Surgery is performed with the assistance of a real-time remotely controlled robot with enhanced sensing capabilities. The patient has access to high quality healthcare, including in remote areas, where there is a lack of medical personnel to perform the needed medical intervention. The patient has now his health condition improved.

4.1.5 Potential requirements

KPIs for medical robotics have been investigated in a number of papers and experiments, which show large variations of reported target values [i.2], [i.37]. The required KPIs for remote surgery are shown in table 1.

Table 1: KPIs for remote surgery

Data type	End-to-end latency	Jitter	Data rate	Packet loss
Vital signs	< 250 ms	N/A	< 10 Kbps	$< 10^{-3}$
3D camera flow	< 100 ms	< 30 ms	20 Gbps	$< 10^{-2}$
Biopotentials and electrophysiology measurement	< 250 ms	N/A	70 Kbps - 1,5 Mbps	$< 10^{-3}$
Haptic feedback	1 - 100 ms	< 2 ms	< 1 Mbps	< 1 % - 10 %
NOTE: The values above are understood as end-to-end.				

4.1.6 Physical environment

For sensing purposes (sensors in the robot/medical cart analysing the human tissues), the channel is very short range, typically line of sight and may have specific characteristics linked to body-centric communications in THz range. For connectivity between the robot/sensors and the THz hotspot, the propagation channel is indoor, short to medium range, with very low mobility, and may have specific characteristics linked to the healthcare facility environment (e.g. metal clutters due to medical equipment). For connectivity between the human operator and the THz hotspot on the controller site, the propagation channel is indoor, short to medium range, with very low mobility.

4.1.7 Enabling technologies

Telesurgery has been already successfully performed in a swine using a 5G network in China, however, the average round trip delay of the 5G network during the operation was 114 ms [i.1]. This value should nevertheless not exceed 100 ms, which is the maximum latency agreed in the literature to avoid major surgical accuracies in medical equipment handling [i.4].

Considering the integration of other technologies such as Artificial Intelligence (AI), AR, haptic and tactile technology to support the remote medical intervention, the throughput in the network should become even higher and required latency much lower than 100 ms (haptic technology may require a latency less than 1 ms [i.5], although higher values up to 50 ms or even 100 ms were reported by different sources [i.2]). A high throughput and low latency communication network based on THz communications could enable this particular use case.

Other enabling technologies include edge computing for reduced network latency, AR/VR and/or haptic and tactile technologies for remote operation, and possibly AI support to manage the patient data and help in the medical intervention.

4.2 Use case on in-airplane or train cabin entertainment

4.2.1 Description

In-cabin entertainment for modern airplanes and trains demands ever increasing bandwidth and data rate requirements. Examples of such services include video streaming, gaming, video conferencing, and internet browsing, in addition to real-time updates on the journey and airplane/train status [i.6], [i.7]. Some of the main challenges to address towards realizing such demanding in-cabin services are [i.8], [i.9] and [i.10]: high data rate requirements, high crowd density (e.g. a double-deck train cabin may include 180 passengers), low latency (for e.g. gaming), and GHz-level bandwidths (for e.g. video streaming). These challenging requirements motivate the exploration of the THz bands.

A cellular hotspot using THz technology can be installed in an airplane or train cabin to provide entertainment, internet connection and real-time information to the passengers, as shown in figures 3 and 4. The THz link allows for higher capacity, higher data rate and lower latency communication compared to a traditional Wi-Fi® hotspot. The backhaul connection to the internet can be provided by either ground base station or Non-Terrestrial Networks (NTN). A local server/cache in the airplane or train may be used to minimize the backhaul transmission. The intra-cabin local communication could be routed by the hotspot directly. The devices inside cabin may also directly discover and communicate mutually over the THz spectrum allocated by the hotspot. To ensure efficient and secure transmission, preconfigured beams are cast to each seat, and directional transmission is used to minimize interference with airplane or train electronics. If needed, the radio coverage to other areas of the cabin may be provided by different beams or different frequency layers.

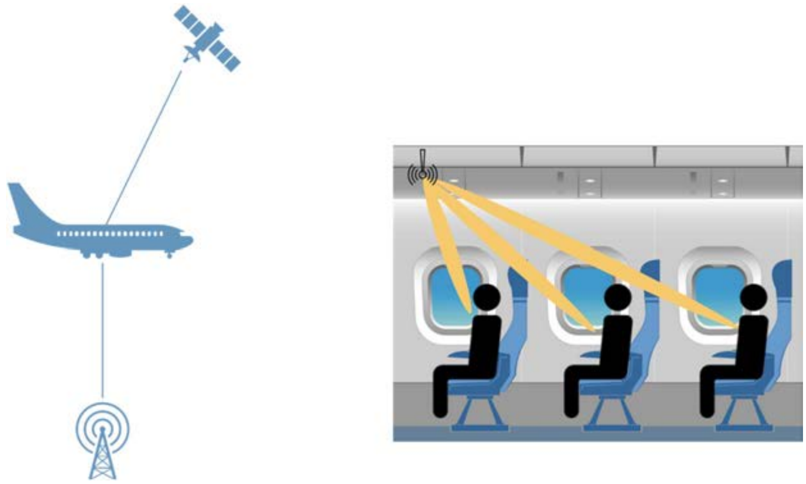

Figure 3: In-airplane or train cabin entertainment

Figure 4: In-train cabin entertainment

4.2.2 Pre-conditions

The in-airplane or in-train cabin hotspot is installed at a location that ensures good coverage in a short range. The airplane or train is connected to the ground base station or NTN as backhaul for the hotspot. UEs are authorized to use the cellular service provided via the hotspot. The backhaul and authorization may not be needed for intra-cabin local communication. If the THz spectrum is shared with Earth-Exploration Satellite Service and Radio Astronomy Service, following the investigations in [i.11], aircraft windows should be non-transparent for the relevant carrier frequencies to avoid harmful interference.

4.2.3 Service Flows

- User Equipment (UE) in the airplane or train cabin discovers the THz hotspot by radio link measurements.
- UE connects to the hotspot and registers with the cellular network.
- UE connects to internet via the hotspot.

For local communication inside the cabin, the traffic is routed by the hotspot. Registration and routing to ground cellular network are optional in this case.

Users in the train or airplane cabin engage in activities with high data rate requirements, such as video streaming, and low latency requirements such as video conferencing and gaming.

4.2.4 Post-conditions

UE enjoys in cabin entertainment based on high speed and low latency wireless communication over THz via the hotspot. UE also enjoys real-time, multi-media (e.g. video and audio) information about their journey and the status of the plane or train.

4.2.5 Potential requirements

- The UE should support discovering, connecting to and communicating with the THz hotspot.
- The UE should support prioritizing in-cabin THz hotspot in connection and communication.
- The airplane or train should be connected to the ground base station or NTN as backhaul for the hotspot.

4.2.6 Physical environment

The use case works in the airplane or train cabin. However, with respect to co-existence with Earth-Exploration Satellite Service and Radio Astronomy Service the situation for airplanes differs from the one for trains. Whereas the train application is covered by the sharing studies carried out in the framework of WRC 2019 [i.12], the airplane applications require a separate sharing study or corresponding measures as indicated in [i.11].

4.3 Use case on cooperative mobile robots

4.3.1 Description

During the last few centuries, human society has obviously benefited greatly from increased automation. Cooperative mobile robots promise even further benefits in terms of sustainability, productivity, etc.

Mobile robots may include various forms of guided vehicles, such as Automated Guided Vehicles (AGVs), laser guided vehicles, drones, etc. A mobile robot may be autonomous or remotely controlled, for example by a centralized controller or by a human. Remote control or coordination requires network coverage in the service area. Self-organized cooperation between autonomous mobile robots may include real-time distributed learning and joint inference. One or more robots may also work cooperatively with humans or human-controlled robots to accomplish a joint task.

A simple example of cooperative mobile robots is cooperative carrying, where a group of robots cooperate to carry an item [i.13], including cooperative carrying of parts, goods, containers, etc., for example between a warehouse and a production line, or between stations in a production line.

A more elaborate example application of cooperative mobile robots is their application in **flexible software-defined manufacturing and logistics**. In this example, mobile robots collectively work together to accomplish a task to support a flexible and dynamic production system, with robot to robot and robot to human interaction. Unlike a traditional pre-planned production line, flexible manufacturing can be dynamically adapted, e.g. to meet time varying market demands and customer preferences. The manufacturing process can flexibly evolve over time and be optimized for new goods. To that end, flexible manufacturing needs to support (multi-)task capability, varying requirements, and requires multi-modal information fusion. Furthermore, a software-defined factory may need to be rapidly deployed and redeployed in different locations, making it essential to ensure that all equipment and machines can be easily transported and connected to necessary utilities. To overcome these challenges, solutions such as modular designs, standardized connections, and new network architectures need to be devised.

The challenges for remote control of robots, for example a group of drones as illustrated in figure 5, include the delay and the reliability for intra-group collaboration. In today's systems, delay and reliability issues are largely caused by devices contending for the limited radio resources. This results in queuing of control communication, waiting for base station scheduling. THz has rich spectrum resources and can help to minimize the contention and queuing. Utilizing THz communication within the group of robots allows for low latency and ultra-reliable communication.

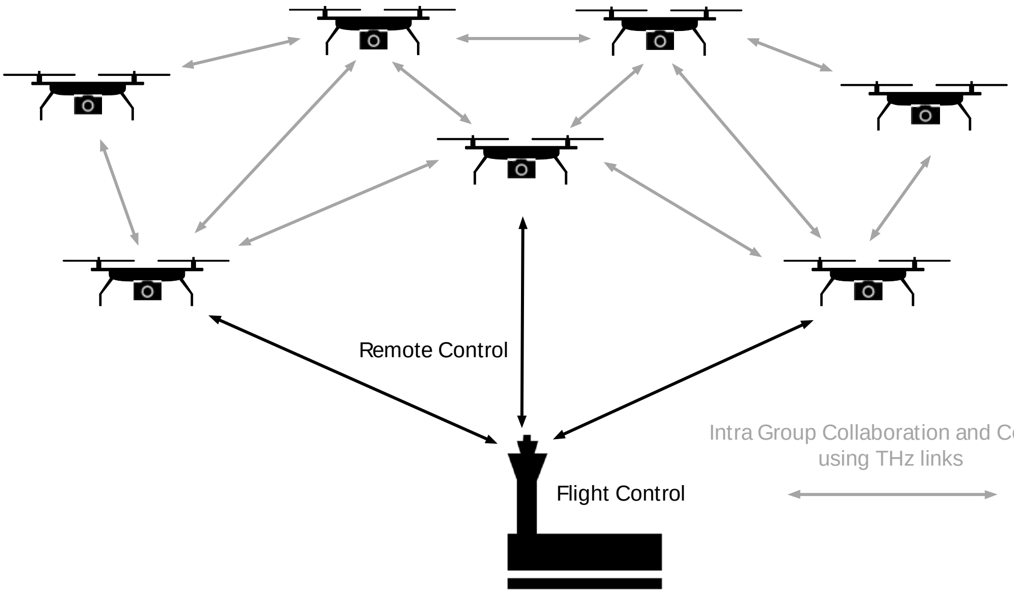

Figure 5: Drone remote control and intra group collaboration

Communication data flows between many robots and the network or directly between robots may include high-resolution sensor data and actuator control, which also requires the very high data rate, reliability and capacity, and the low latency, that the wide bandwidths of the THz spectrum can provide. The combination of very high data rates, reliability, and low latency is needed to guarantee the safe operation and driving of mobile robots, such as AGVs [i.14] and [i.15]. In case of distributed processing, some decisions may be taken autonomously in the robot, while others need support or commands from a network-side application server, creating a need for data exchange in both directions as well as between robots.

Cooperative mobile robots also require high accuracy sensing and localization, which can be provided in the THz spectrum. The mobile robots not only need to sense and localize themselves in a static environment, but also in relation to other mobile robots, humans, and moving objects. In the flexible manufacturing and logistics example, a group of cooperative robots assembling or jointly carrying an object may require high-precision sensing and localization to complete one or more tasks successfully.

4.3.2 Pre-conditions

- The mobile robots are under THz network coverage.
- The mobile robots are connected to a network-side application for some level of centralized control of the robot collaboration.
- The mobile robots are pre-configured with tasks and objectives for some level of autonomous operation and collaboration.
- The necessary objects of the tasks (raw materials, tools, etc.) are present.

4.3.3 Service Flows

One or more tasks are started by the network-side application.

- Network-side application sends data and commands to mobile robots.
- Mobile robots send data and commands to network-side application, e.g. sensor data, actuator data, etc.
- Mobile robots send data and commands to each other for cooperative actions, distributed processing, etc.
- Mobile robots perform actions and complete task(s).

4.3.4 Post-conditions

The task(s) is/are successfully completed in a manner that is safe and that provides benefits in terms of productivity and sustainability.

4.3.5 Potential requirements

- The system should provide sufficient data rate for the network to robot links, as well as for the robot-to-robot links. For example, 600 Mbps - 3 Gbps may be required for video processing offloading (depending for example on e.g. the video quality, or number of frames per second) [i.54] and [i.17].
- The system should provide low enough latency and jitter for the network to robot links, as well as for the robot-to-robot links. For example, less than 0,5 ms deterministic latency may be required for control applications [i.17].
- The system should provide very high reliability, e.g. up to 99,9999999 % [i.17], for the network to robot links, as well as for the robot-to-robot links.
- The system should provide sufficient absolute and/or relative positioning accuracy. For example, below 20 cm for both vertical and horizontal positioning with less than 15 ms latency for acquiring real position update may be required for AGVs [i.20], and sub-cm localization with down to 0,1 ms latency may be required for cooperative robots [i.18].
- Distance between a part of a robot (e.g. robot arm) and a human/object should be sensed with sub-cm level accuracy and with down to 0,1 ms latency [i.18].
- Translational mobility up to 10m/s should be supported [i.17]. Depending on the robot type, also rotational mobility may need to be supported.
- Communication service availability: The system should be able to provide a communication service availability of 99,9999 % within the service area [i.17].
- Security/Trustworthiness.
- Safety of humans near the robots.

4.3.6 Physical environment

The primary physical environment for cooperative mobile robots is **indoor**, for example a factory floor. A secondary physical environment is a dense outdoor deployment, e.g. a harbour, a courtyard, etc.

Low mobility, e.g. pedestrian up to 3 km/h, can be expected in a typical indoor scenario, especially if humans are present. In some scenarios, e.g. involving logistics, higher speeds can be expected, e.g. up to 30 km/h. In addition to translational mobility, robots may experience rotational mobility

Link distances are expected to be less than 100 m [i.19].

4.3.7 Enabling Technologies

The use of THz RIS can enable the efficient re-use of the wireless channel for directional THz communication links in the same local area. This can greatly increase the total amount of throughput available for a given area and enables THz technology to provide a feasible alternative to fixed network infrastructure, for example in a flexible software-defined manufacturing and logistics setting, as shown in the example of figure 6 and as analysed in [i.21]. The incorporation of RIS in the THz wireless will enable realizing the full potential of the technology not only in future mobile manufacturing environments, but any scenario where future dense and very high bitrate devices are envisioned to be present. Beyond the magnitude of available spectrum, this approach promises spectrum efficiency, agility, and directionality, pivotal for the seamless orchestration of a dense network of devices in future demanding use cases, particularly where Machine-to-Machine (M2M) communications are expected to greatly increase.

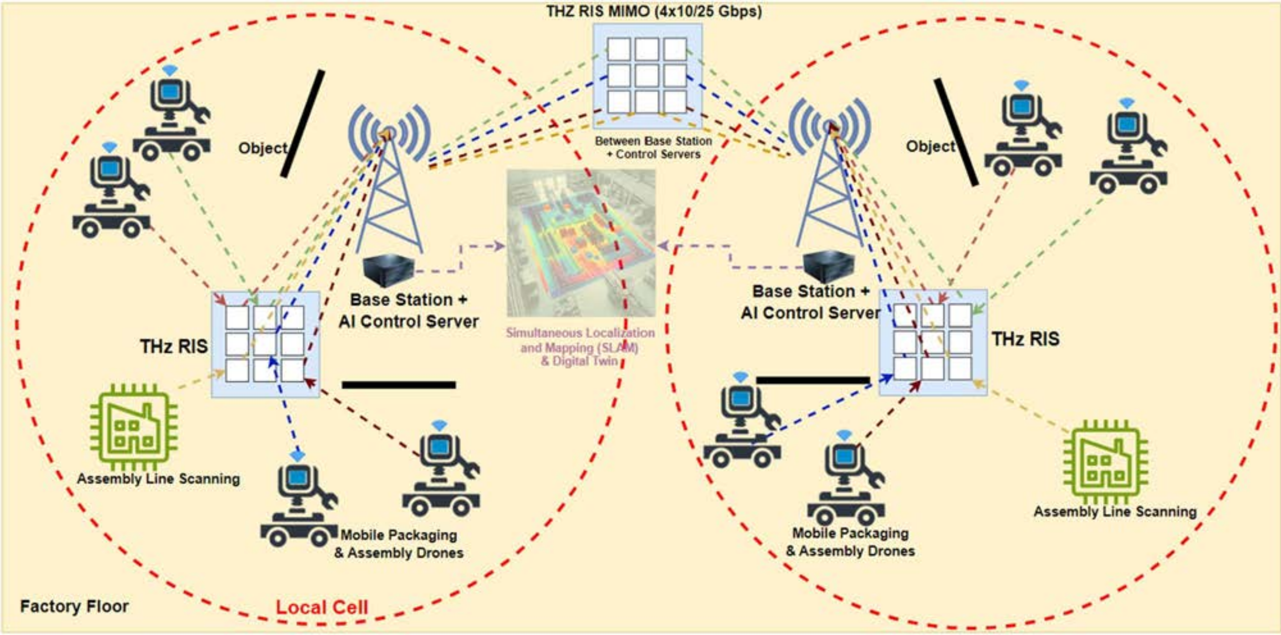

Figure 6: Diagram showing robot to server communication utilizing a THz RIS and server-server connection between local cells using THz RIS multiple input multiple output communications

A local edge server may receive and process high bandwidth Simultaneous Localization And Mapping (SLAM) sensing data from the robots in real-time, for example to provide digital twin representation of a manufacturing plant.

4.4 Use case on hazardous material work

4.4.1 Description

Chemical and hazardous material handling is a known use case in robotics. Using robots to manipulate radioactive, toxic, volatile, or highly explosive material shields human workers from exposure to dangerous environments. Specifically designed robots also have the capability of operating in environments inaccessible for humans, to have access to sensing information beyond human capability, to have precision or implement actions beyond human skills.

The role of THz in such scenarios is central. On one hand, using THz allows collecting and exposing information beyond human sensory capabilities. THz spectroscopy for example has been widely used for chemical detection and identification, pollutant gas detection, pesticide and antibiotic identification [i.22]. On the other hand, real-time high resolution video streaming in THz bands is possible at remote and/or controller sites, at a quality level that cannot be delivered by actual systems.

Societal benefits include protection of human health and improved industrial processes.

Figure 7: An example of remote manipulation of hazardous material

4.4.2 Pre-conditions

Remotely controlled robots exposed to hazardous material or environment are equipped with sensing and communication capabilities, as depicted in figure 7. The human operator console on the controller site, the remotely controlled robot and all other involved equipment in the plant (e.g. sensors) have access to very high throughput connectivity (e.g. via a THz indoor hotspot). The remote and controller sites are connected through a communication link with guaranteed latency and throughput.

4.4.3 Service Flows

- The remotely controlled robot retrieves hazard monitoring information beyond human capability and high-resolution video stream of the hazardous site.
- Sensory data is processed and transferred via a network supporting very high throughput/very low latency and ensuring data security.
- At the controller site, the human operator can visualize high-resolution video stream of the robot operations and can pilot the robot.

4.4.4 Post-conditions

Extremely precise handling of hazardous material or conducting missions in hazardous sites can be done without endangering human health.

4.4.5 Potential requirements

For this use case, part of the target KPIs may highly vary depending on the hazard type.

4.4.6 Physical environment

For sensing purposes (hazard monitoring) and communication within the hazard site, the channel is short to medium range, possibly line of sight and may have specific characteristics linked to the environment (e.g. indoor factory) or hazard type (e.g. specific absorption patterns in case of gas presence). For connectivity at the controller end, the propagation channel is indoor, short to medium range, with very low mobility, and may have specific characteristics linked to the industrial setting (e.g. metal clutters, presence of industrial equipment).

4.5 Use case on remote education

4.5.1 Description

4.5.1.1 Immersive remote education

Remote presence and interaction may fundamentally change the field of education for students worldwide. Immersive classrooms [i.23], [i.24] and [i.25] equipped with eXtended Reality (XR) and sensing infrastructure and devices can provide a personalized learning or recreational experience, where participants can interact with and within remote environments in a natural and intuitive way. In a similar manner, remote hobby/experience activities can be conducted in remote or inaccessible sites. Such remote immersive presence may take place through XR, interactive robotics or holographic telepresence, among other modalities. The role of THz in such scenarios is central, enabling high precision sensing and localization, as well as low-latency, high-throughput data rates to fulfil the real-time requirements.

The societal benefits from immersive education in a remote setting include [i.26]:

- Improved accessibility to novel and high-quality didactical material/settings and educational infrastructure, addressing some of the logistics and cost restrictions many schools currently face.
- Seamless and engaging interaction among participants in multiple locations, which is challenging to achieve in current video-conference-dominant remote schooling.

Immersive classrooms can materialize in two main ways:

- Partially remote or hybrid where, for example, the teacher is present on-site, and the students attend remotely from several locations such as activity centres and home, as illustrated in figure 8. The on-site location can either be indoors or outdoors (as in figure 8).
- Fully remote, where all participants interact virtually. Physical school infrastructure may or may not be required in this setting, as discussed below.

Interaction in immersive classrooms can take place in two main ways:

- Co-presence: where the participants engage in group activities and experience the class as if they are sitting together, either in a partially remote or fully remote classroom.
- Digital twin: where remote participants perform group projects and lab experiments remotely through a digital twin. The infrastructure may be either fully virtual or physical.

4.5.1.2 The role of THz and other multi-sensor modalities

The specific technology and devices for the target classroom are chosen depending on the type of remote setting and interaction described above. The high precision sensing and localization capabilities of THz make it amenable to partially remote, co-presence classrooms, which is the focus of the current description.

THz based sensing can characterize the surrounding environment - including the weather, landscape, flora, fauna, as in figure 8 - with high precision given the very fine spatial resolution awarded by the tiny wavelengths [i.23]. Furthermore, THz based sensing can enable seamless interfacing with the human agents participating in the remote setting by enabling gesture and activity recognition, as well as highly accurate positioning and localization [i.23].

Other enabling technologies helpful to materialize the target immersive classroom are XR, holographic telepresence, sensor fusion, Artificial Intelligence (AI), and autonomous robotic navigation, where THz play a major role. For example, in figure 8 the on-site teacher can interact with the remote students through avatar robots, which can for example render the actions and point of view of remote participants into autonomous motion. As such, these robots act as physical avatars of the remote attendees and also have sensing capabilities. Remote control of the avatar robot is also possible for example to accomplish certain gestures, participate in experiences, or manipulate objects. In a different setting, remote participants could be projected holographically into the on-site location. To enable the desired interaction, remote students are equipped with XR headsets and sensors or remote controllers, which allow them to:

i) visualize the on-site location and the other students' and teacher's gesture and motion; and

ii) provide feedback to other participants.

THz sensing can enable the precise characterization of the on-site environment and the teacher's motion and gestures, as well as the low latency data transfer required. One of the key aspects for XR, which remote attendees require, is that it involves interactive experiences where the entire perspective of the user may be communicated via the network. In this scenario, moreover, the characteristics of the on-site environment should be communicated via the network as well.

Societal benefits of the described use case include access to high quality education, to immersive experiences and hobbies, and overall improved quality of life for everybody, anytime, anywhere.

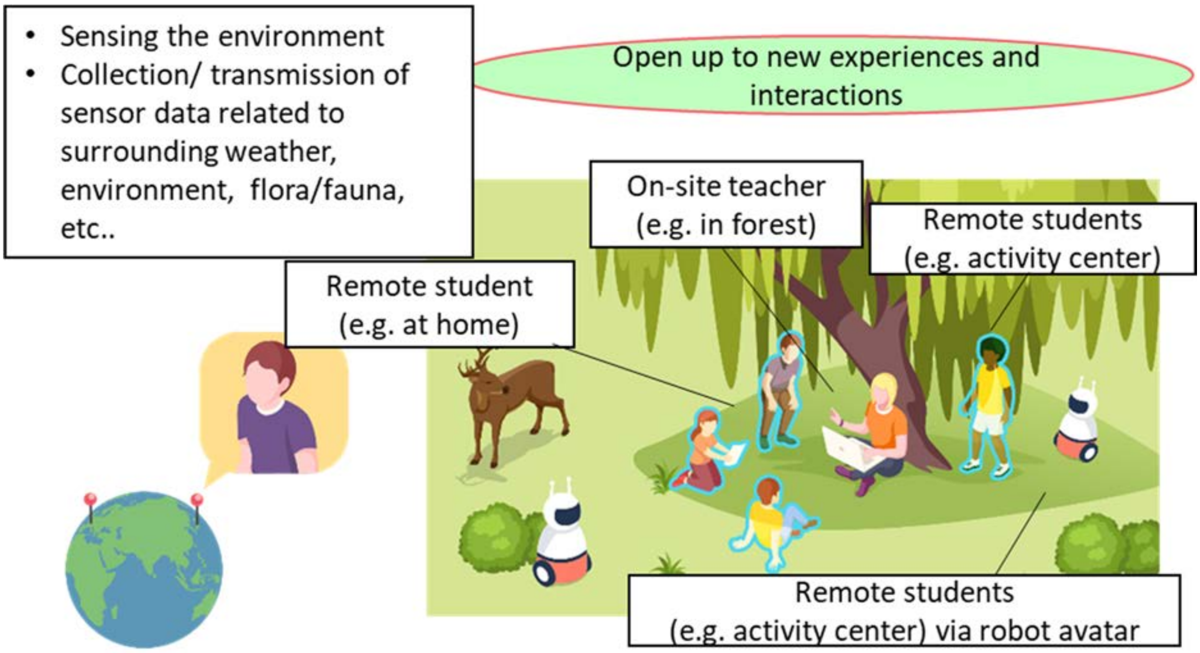

Figure 8: An example of remote education scene

4.5.2 Pre-conditions

- The educational/recreational facilities should be equipped with THz-based infrastructure capable of **sensing and communication**.
- Interactive **remotely controlled robots** may have access to such facilities to act as physical avatars of the remote attendees, and to engage in data collection.
- Facilities may also be equipped with **devices that can project virtual avatars** of remote attendees (e.g. hologram).
- Remote attendees are equipped with **various interfaces** allowing them to interact with the cyber-physical environment in real time including sensors, remote controllers and XR headsets. The latter, in tandem with, for example, haptic feedback devices, can allow attendees to engage in real-time interaction with objects and other participants.
- Both on-site and remote locations should have **coverage from a network operator providing bi-directional connectivity** with low latency and very high throughput.

4.5.3 Service Flows

An example of service flows is depicted in figure 9:

- At the educational/recreational facility, various types of sensors collect data from human agents and the surrounding environment.
- The collected data should be parsed and processed to extract relevant information, such as attendee positions and their point of view (important for correct VR rendering), gestures and actions executed by the attendees, motion from the robotic avatars, etc. Some of the processing can be done on-site, computationally intensive tasks should be offloaded to the cloud.
- Bi-directional high-throughput links allow remote attendees to control interactive avatar robots with sensing capabilities.
- Bidirectional high throughput links allow projecting on-site virtual avatars of the remote attendees and transfer of sensor data.

The communication system in figure 9 may be for example structured as in figure 10.

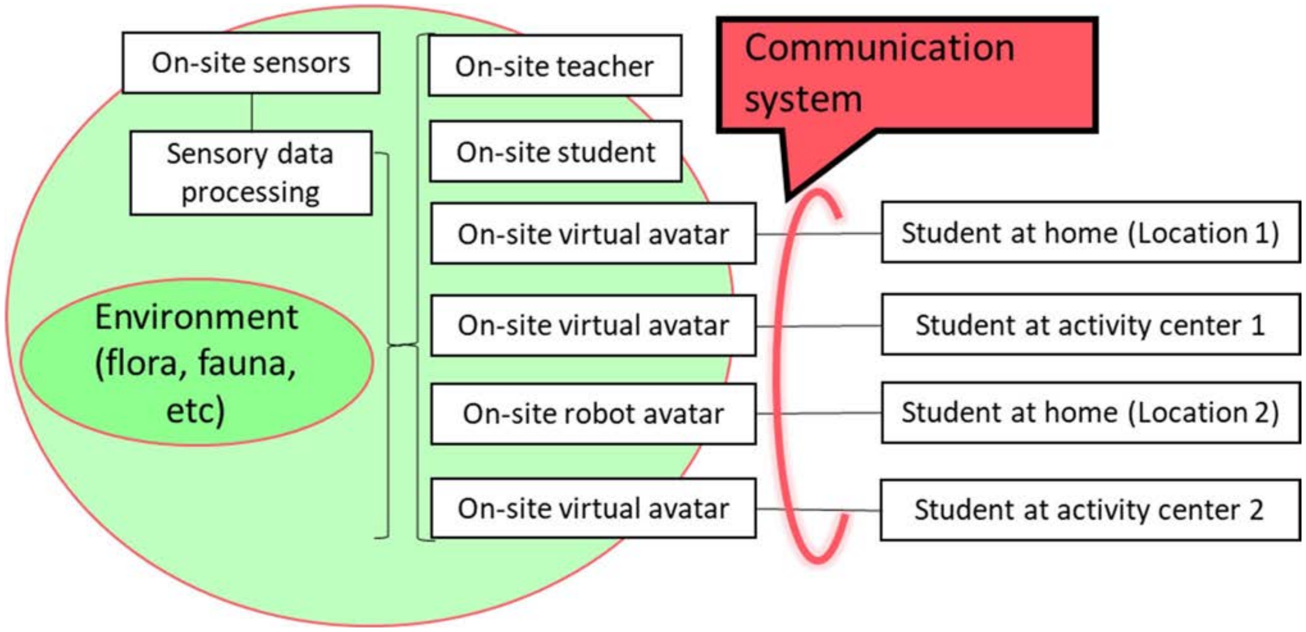

Figure 9: An example of service flow for remote education

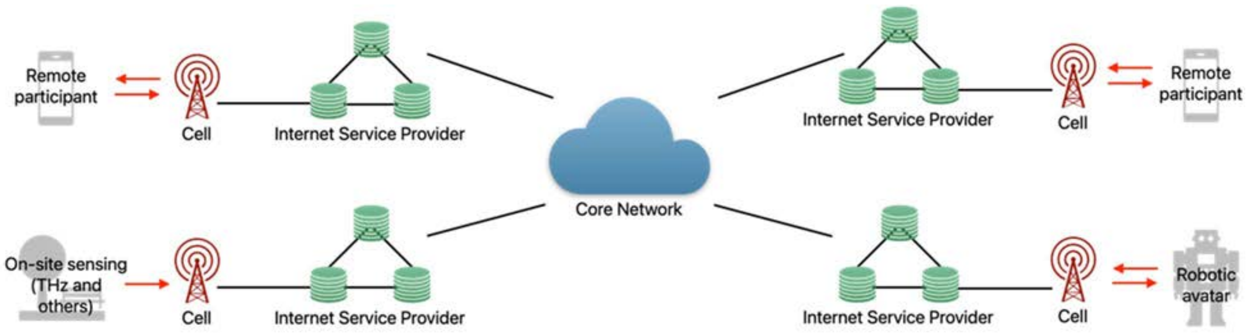

Figure 10: An example of a communication system [i.27]

4.5.4 Post-conditions

Attendees engage in seamless remote interaction, enabling high-quality, accessible educational or recreational experiences.

4.5.5 Potential requirements

Potential requirements for this use case involve:

- The system should support accurate coordination and integration of THz sensing capabilities with communication protocols.
- The system should support computation offloading scheduling and coordination, such as that required by remote rendering or XR.
- The system should support AI functionality integration in the network architecture for seamless and efficient use.
- The system should support simultaneously enabling of high data rate and low latency as discussed in table 2.
- The system should support improved data privacy and security, which is not guaranteed by current networks.

- The system should support the KPIs in table 2 (minimum/maximum requirements may vary depending on the target quality of experience).

Table 2: KPIs for remote education

Data type	End-to-end latency	Data rate
3D holographic display of on-site virtual avatar	< 1 ms	Up to ~2 - 4 Tbps [i.51] and [i.28]
Immersive AR/VR at remote location	10 ms	1 Gbps (without compression)
Interactive avatar robot control	< 300 ms	N/A
Haptic feedback for robot control	50 - 100 ms	< 1 Mbps

4.5.6 Physical environment

- Mobility: This use case involves limited mobility (at most, pedestrian-level speeds, or < 5 km/h [i.29]) and can be implemented in various settings (indoor or outdoor educational facility, etc.).
- Dimensions: Both indoor and outdoor immersive classrooms are targeted. A rule of thumb used for traditional indoor classrooms is that each student should take at least 2,5 m^2 [i.30], which is also considered in this use case to create an immersive environment where remote participants experience the class as if they are sitting together. The dimensions of outdoor environments will depend on the education experience of interest but may require higher square footage than indoors.

4.5.7 Enabling technologies

- THz sensing and localization: THz sensing exploits the wavelength in the order of micrometers and the frequency-selective resonances of various materials in the environment to extract unique information about the current situation [i.31]. Furthermore, in contrast to infrared radiation, THz waves are less vulnerable to environmental factors such as ambient light and smoke, making them amenable for the multi-setting educational scenarios outlined above (e.g. indoor and outdoor [i.32]).
- XR, including Virtual Reality (VR) and AR to provide seamless interaction in the cyber-physical world [i.33].
- Artificial Intelligence to render the sensing data and infer relevant information (e.g. activity and gesture recognition, high precision positioning in Line of Sight and Non Line of Sight scenarios, etc.).
- Autonomous robotics: for example, THz-based SLAM and localization [i.34], [i.35] as well as advanced robotic navigation [i.36].

4.6 Use case on fixed point to point wireless applications

4.6.1 Description

4.6.1.1 Use case on fixed wireless X-haul transport

Distributed RAN Mobile Transport networks are traditionally used for backhaul connecting mobiles sites and cells to core network. The links in the transport network uses a mix of fibre and radio connections complementing each other. Figure 11 below shows the mix of technologies currently used in the backhaul network. According to the GSMA and ABI Research report "Wireless Backhaul Evolution" [i.39], microwave and millimetre wave backhaul will continue to be used by a majority of global macro and small cell backhaul links until at least 2027, followed by fibre as the second most popular option.

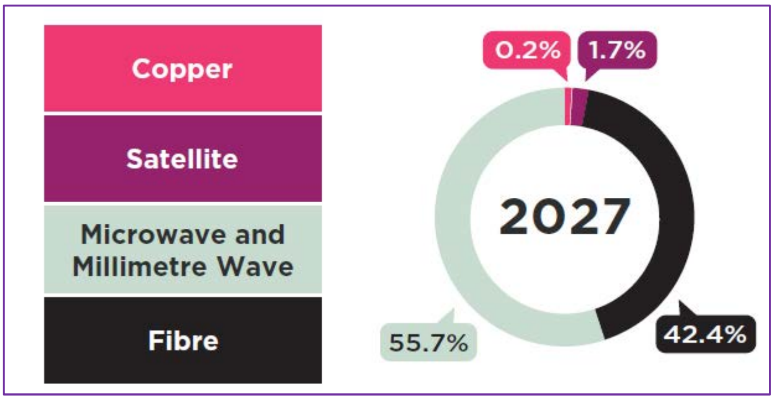

Figure 11: Global macro and small cell backhaul links by technology 2021 to 2027 (Source: GSMA and ABI Research report "Wireless Backhaul Evolution" [i.39])

New RAN architecture emerged in recent years in which the RAN functions are disaggregated and split between a Centralized Unit (CU), a Distribution/BaseBand Unit (DU) and the Radio Unit (RU). The Backhaul is still used to connect aggregated traffic at a CU, that is connected to a number of DUs, to a Core network. The Midhaul network is used to transport the High Layer Splits (HLSs) traffic between a CU and the DUs, while the Fronthaul network is used to transport the Low Layer Splits (LLSs) traffic between DU and a cluster of RUs that are connected to it. Figure 12 below shows high level overview of D-RAN and C-RAN architectures.

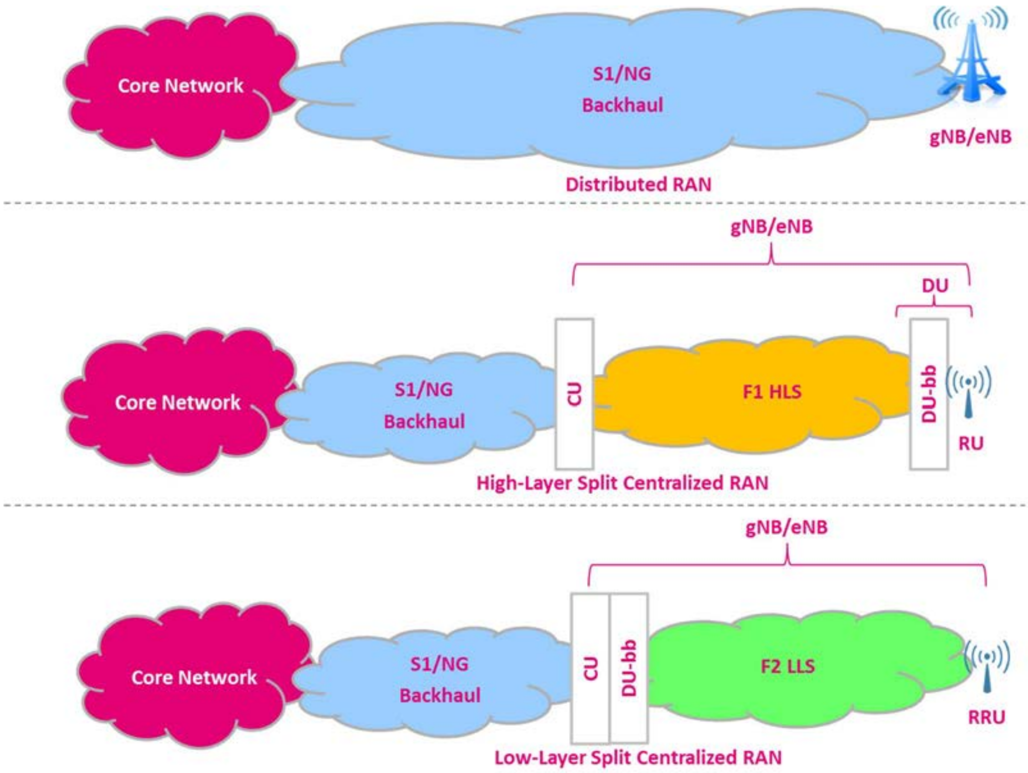

Figure 12: Distributed and Centralized RAN Architectures

Currently used and allocated spectrum for fixed point to point wireless links are shown in figure 13.

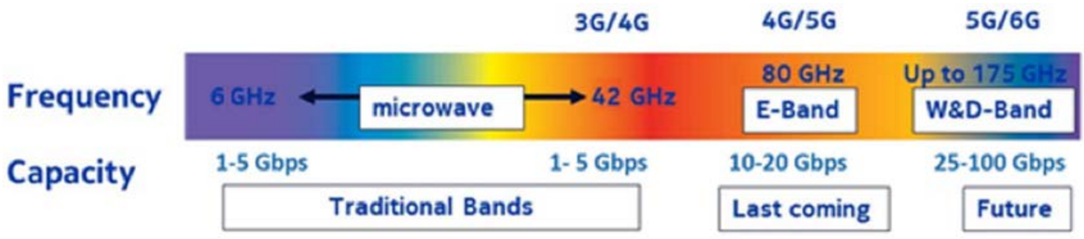

Figure 13: Current bands allocation for fixed point to point radio links and their corresponding capacities

Traditional backhaul and F1-based MidHaul (namely, Option 2 HLS [i.40]) present equivalent capacity and latency requirements. These transport links need to keep up with the increasing traffic demands and low latency requirements for the 5G and future generation mobile services. However, for the LLS traffic in the Fronthaul links require higher capacity and stricter low latency in order to support RAN advanced functionalities such as mMIMO, Coordinated Multi-Point (CoMP), etc. Wireless transport links in the THz band can support these higher capacity requirements in the order of 100 Gbps due to the large spectrum availability allowing channel spacing of up to 5 GHz and by applying advanced multiplexing techniques such Line-Of-Sight MIMO (LoS-MIMO) [i.41] and Orbital Angular Momentum (OAM) [i.42].

Example of fronthauling and backhauling in mobile network architecture is shown in figure 14.

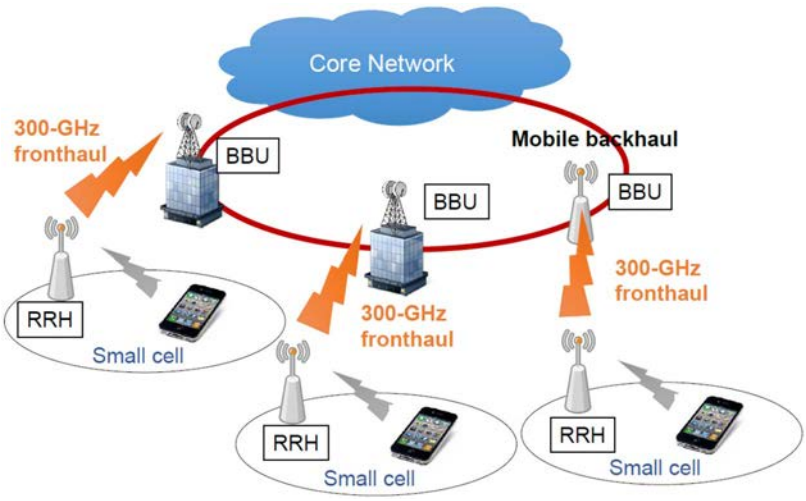

Figure 14: Example of fronthauling and backhauling in mobile network architecture (Source: Report ITU-R SM. 2450-0 [i.12])

4.6.1.2 Enterprise point-to-point link

Enterprise communication network is used to carry non-mobile network data traffic, but rather enterprise local area network and data information related to a specific vertical industry. Example of Enterprise point-to-point link is the specific scenario of railway applications described below for bridging various railway information in the railway communication infrastructure across platforms. Other applications of Enterprise point-to-point links are used to bridge local networks between 2 offices across buildings.

The railway communication infrastructure refers to communication nodes installed on the trackside equipment of the station and the communication between them is fixed link. For the Infrastructure-to-infrastructure communication scenario for railways [i.10], it is a typical application for high-quality communication based on fixed-link. In the future, railway communications are required to evolve to various high-data-rate applications (e.g. [i.6] and [i.7]). Examples of such applications include [i.43]:

- **Train operation information** that provides critical information regarding voice and control signalling, on-route train performance, and train equipment status.
- **Journey information** that dynamically updates journey information for all passengers via multimedia.

- **On-board and wayside High-Definition (HD) video surveillance** that is critical for safety and security concerns.
- **Real-time train dispatching HD video** between train and Train Control Centres (TCCs) required for train dispatching and driverless systems.

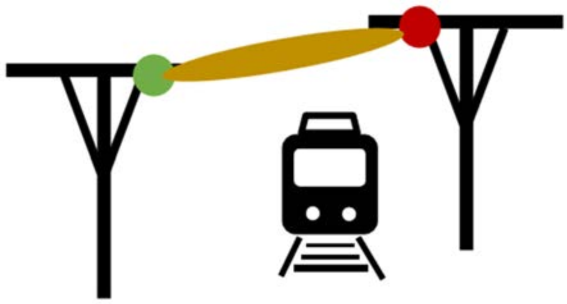

Figure 15: Infrastructure-to-infrastructure scenario

As illustrated in figure 15, **Infrastructure-to-infrastructure** (HD video and other information in real-time transmitting among various infrastructures) [i.9], describes HD video and other information in real-time interaction among multiple cameras and Access Points (APs), e.g. a high-date-rate wireless backhaul, supported by bi-directional streams with very high data rates and low latencies.

4.6.2 Pre-conditions

Nodes of the THz transport links are mounted and aligned within ±0,5° (this could be relaxed to within ±5° if auto-alignment techniques are applied). The transmitter and receiver will be installed ensuring the first Fresnel zone to be free of any obstructions. These links should operate in a coordinated or self-coordinated link assignment to avoid inter links interference.

4.6.3 Service flows

The prime application of the wireless transport is for mobile X-haul conveying mobile traffics from 3GPP defined interfaces as E1, x2/xn, F1, as well as Open Radio Access Network (ORAN) specified fronthaul interface traffic.

The Backhaul connects aggregated traffic at a CU, that is connected to multiple DUs, to a Core network.

The Midhaul network transports the HLS traffic between a CU and the DUs.

The Fronthaul network transports the Low Layer Splits traffic between DU and a cluster of RUs that are connected to it.

Other traffics are also envisaged to be transported over these THz wireless transport links such as enterprise private traffics, security cameras etc.

4.6.4 Post-conditions

Based on terahertz links, wireless transport links will fulfil the requirements of low latency and ultra-high capacity in the order of tens of Gbps.

4.6.5 Potential requirements

Potential requirements are summarized in table 3.

Table 3: Typical requirements for fixed point to point wireless applications

Communication distance	Up to 1 km
Throughput	• For X-hauling: Up to 100 Gbit/s • For enterprise point-to-point links: up to 20 Gbit/s (user experienced data rate up to 100 Mbit/s)
Physical environment	Outdoor
Required BER	10^{-12} [i.38]
Latency	• For Midhaul and Backhaul (one way latency) – 1 ms - 50 ms service dependent – 0,5 ms for URLLC services • For Front haul (one way latency) – 25 µs to 100 µs depending on deployment scenario • For enterprise point-to point links – 1 ms
Availability	• For Midhaul and Backhaul – 99,9 % - 99,99 % non URLLC services (depending on operators' strategy) – 99,999 % URLLC services • For fronthaul – 99,999 % • For enterprise point-to-point links – 99,9 %

4.6.6 Physical environment

Wireless transport links are required to operate in outdoor environment with line-of-sight operation between the transmitter and receiver with in first Fresnel free zone.

4.6.7 Enabling technologies

Advanced technologies such as cross polar interference cancellation, LoS-MIMO, OAM, and band and carrier aggregation are useful for meeting the capacity requirements of X-hauling and enterprise scenarios.

4.7 Use case on mobile wireless X-haul transport

4.7.1 Description

The wireless X-haul transport with mobility describes the X-haul link established between two transport nodes, where the transport node on one side is mobile and the other side is stationary. The communication channel between the two transport nodes is line-of-sight and generally the node on the stationary side is connected to the core network. Based on terahertz links, high-quality communication with low latency and high reliability can be achieved for mobile X-haul transport. This clause discusses the Train-to-Infrastructure communication as a specific scenario of backhaul transport in railway applications.

The infrastructure refers to communication nodes installed on the trackside equipment of the station. Train-to-Infrastructure (T2I) [i.10], describes links between the transport nodes/transceivers of (the wireless local network of) the train and the infrastructures and requires (bi-directional) streams with very high data rates and low latencies (millisecond level) [i.9], [i.8]. Examples of applications include:

- **On-board real-time high-data rate connectivity** for web browsing, video conferencing, video broadcast, etc.
- **Train operation information** that provides critical information regarding voice and control signalling, on-route train performance, and train equipment status.
- **Journey information** that dynamically updates journey information for all passengers via multimedia.
- **On-board and wayside High Definition video surveillance** that is critical for safety and security concerns.

- **Real-time train dispatching HD video** between train and Train Control Centres (TCCs) required for train dispatching and driverless systems.

T2I links appear when the relative mobility of the train and infrastructure is low, such as when a train stops at a railway station, where the transport node on the top of the train can establish a wireless backhaul link with the transport node on catenary masts or the platform.

Figure 16 illustrates the T2I communication scenario of the railway.

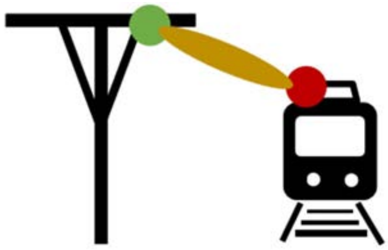

Figure 16: Train-to-infrastructure scenario

Potential requirements to support such applications, including high data rate and huge bandwidth, motivate the exploration of the THz bands. Systems operated at these frequencies are referred as THz communication systems.

4.7.2 Pre-conditions

The infrastructure and train cabin can connect to the network through a THz link.

4.7.3 Service flows

Trains in stations search the surrounding area for transport nodes installed on the infrastructure that can be accessed. A THz link will be established between the transport nodes/transceivers of the train and the infrastructures.

4.7.4 Post-conditions

With the microsecond latency, the European Train Control System (ETCS) level-3, where trains are allowed to communicate with the Train Control Centre (TCC) directly with reliable radio communications, will be realized.

4.7.5 Potential requirements

The following challenges for T2I X-hauling were identified in [i.8]:

- Very high data rate (peak data rate - up to 20 Gbit/s, user experienced data rate - up to 100 Mbit/s).
- Very dense crowds of users (up to 106 devices/km^2).
- Very low latency (down to 1 ms).
- Bandwidth requirements (7,2 GHz to dozens of GHz).

For railway T2I scenario, the wireless link should guarantee close to 100 % availability as well as very low latency. This link will be the main interface between the onboard network and the fixed base station. To this end, a bandwidth of dozens of GHz is required to supply up to hundreds of Gbps data rates. Such high data rates and huge bandwidth requirements form a strong driving force to exploit the THz band, i.e. beyond 300 GHz, where the available spectrum is massively abundant.

4.7.6 Physical environment

For railway T2I scenario, the use case will work in the "Smart rail mobility" environments [i.10].

4.8 Use case on wireless data centres

4.8.1 Description

As datacentres generate large volumes of data, they demand networks with high capacity and efficiency. In this context, Software Defined Networks (SDNs) is an important technology that allows decoupling the control and data planes of a network, allowing for programmable, adaptive, and flexible network management. This means network administrators can shape traffic from a centralized control system and Quality of Service (QoS) policies without touching individual switches. In the case of optical communication, the bandwidth can be adjusted dynamically based on the current load and demands, but it is ultimately limited by the fixed point-to-point nature of wired links, and the static maximum bandwidth for any given link [i.21]. Pure wired data centres are static and cannot be easily reconfigured following the requirements from dynamic traffic conditions. In addition to that the cabling complexity (either copper or fibre) wastes much space and is hard to maintain. The cabling complexity also affects data centre cooling. THz links can provide similar data rates as fibre connections [i.45].

4.8.2 Pre-conditions

In order to apply wireless links in data centres beamforming capabilities are required and includes the following features [i.46]:

- Beamforming capabilities both in azimuth and elevation (position of the antennas are known and need not to be determine in a device discovery process).
- Ceiling reflectors (e.g. aluminium plates or other good reflecting materials, RIS, etc.) to enable connections in case of obstructions between transmitter and receiver.
- Electromagnetic absorbers on top of the racks to prevent local reflection/scattering around the antenna.

4.8.3 Service Flows

- A wireless link needs to be set-up between two racks.
- Mechanically/electronically aligning the antennas based on the known locations of the antenna.
- Link is kept alive as long as the link is required.
- Shut down of the link after it is not needed anymore.

4.8.4 Post-conditions

Some of the fibre links can be replaced by wireless THz links enabling a quick, flexible and reliable reconfiguration of the data centre.

4.8.5 Potential requirements

Data rates similar to those provided by fibre connections are required, i.e. several Gbit/s up to several hundred Gbit/s. It is anticipated that the data centre channel will be line-of-sight, which includes reflecting the signal off an RF mirror. This might require some beam steering, which was out-of-scope of IEEE Std 802.15.3d-2017 [i.47] and IEEE 802.15.3d [i.48]. It can be assumed that the antenna positions are well-known in advance and beam-steering can be preconfigured or fed in as external information. The wireless switch should be competitive to fibre optics in regard to bit errors. A bit error rate of 10^{-12} is required for some links.

4.8.6 Physical environment

Physical environment consists in indoor data centre, intra-rack connections, inter-rack connections, short and medium range. Depending upon the switch configuration and the size of the data centre, ranges of 10 m to 100 m would be in order.

4.8.7 Enabling Technologies

As a further enhancement a RIS can improve wireless communication within data centres, providing ultra-high bandwidth, low latency, and high energy efficiency. RISs' ability to dynamically reconfigure waves and thus wireless links dynamically, when integrated with SDN, can be exploited to dynamically boost the capacity of optical links therefore increasing the flexibility and adaptability of the network. The RIS can be programmed to dynamically adjust the available bandwidth between communicating servers on-demand, allowing for an increase of the total available bitrate between any set of servers during high traffic events (beyond the limit of fixed point-to-point wired links), therefore avoiding the traffic congestion that can occur in the traditional wired network leaf-spine topology. As a result, the overall capacity of the network during periods of peak demand can be significantly boosted. This dynamic management of capacity optimizes network performance, allowing data centres to handle larger volumes of data more efficiently. The THz RIS can also be used to establish alternative communication paths to respond to a communications link disruption, thereby enhancing the overall network resilience. Additionally, THz RIS-based wireless data centres enable the establishment of point-to-multipoint communications, going beyond traditional and inflexible fixed point-to-point wired infrastructure, therefore enabling more flexible and cost-effective network infrastructures and providing the space of the creation of new types of SDN features.

In order to enable the use of RIS, server racks need to be equipped with RIS. In case RIS is used, an SDN controller monitors the network and sends actuation signals through a control plane in order to reconfigure the THz RIS.

4.9 Use case on interactive immersive XR

4.9.1 Description

EXtended Reality (XR) refers to a range of technologies that combine VR, AR and Mixed Reality (MR) to create immersive digital experiences. Immersive here refers to a quality of audio/visual/sensory presentation that exceeds the limitations of the human senses. The immersive audio-visual experience is typically provided using wearables, such as an XR headset, haptic gloves, or glasses, but may also include holographic displays.

Interactive Immersive XR includes real-time interaction with other remote humans, digital representations (avatars) and virtual entities/objects in virtual worlds [i.49].

XR communication has at least three flows:

- flow 1: sensor information, e.g. from motion sensors, RF sensing, etc.;
- flow 2: video/audio media;
- flow 3: control signaling, e.g. haptic or actuation feedback control.

Both flow 1 and 2 require ultra-low latency. Flow 2 requires high data rate and flow 1 requires high reliability in addition.

XR may be supported in different forms, e.g. as shown in figure 17 per 3GPP study on eXtended Reality (XR) in 5G [i.50].

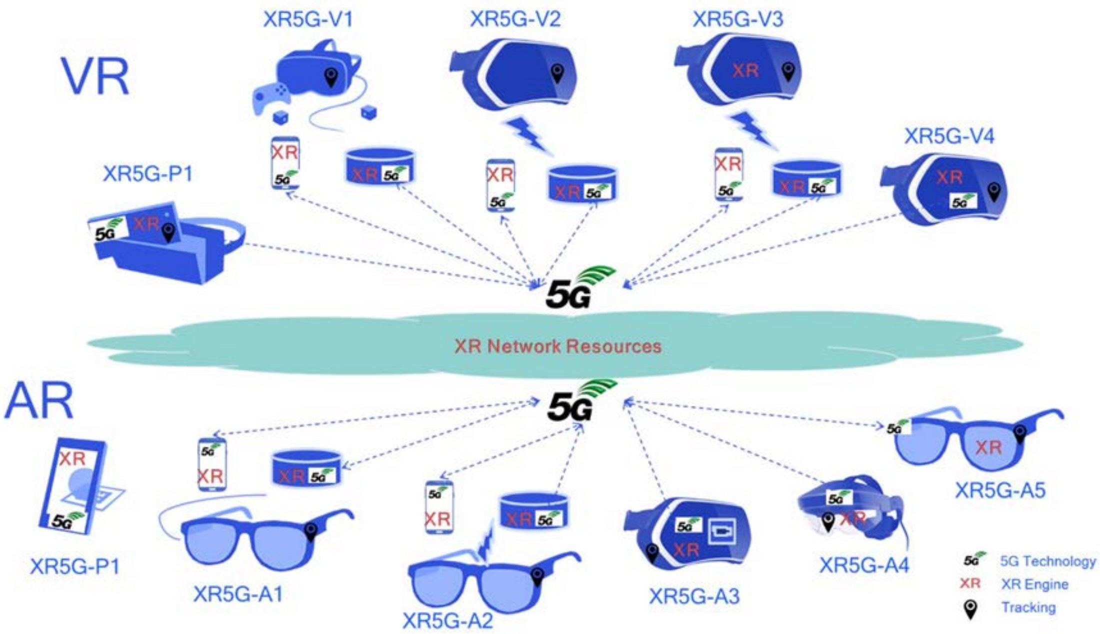

Figure 17: XR Form Factors
(Source: ETSI TR 126 928 [i.50], figure 4.9.1)

Control input from the XR user may be provided in flow 1 through physical controllers, e.g. a handheld controller, but also via gestures, body pose, or voice. To this end, interactive immersive XR may require real-time gesture and body pose detection as well as localization, for which THz spectrum can be used. Besides explicit control input, the user's point of view should also be determined in flow 1 to correctly render the video/audio media that is delivered in flow 2 [i.51]. User viewpoint estimation can also rely on inertial or THz sensing. Another important aspect of interactive immersive XR gaming is the tactile and haptic feedback in flow 3, which may be implemented in a physical controller, body-mounted sensors/actuators, etc.

Furthermore, the very high data rates and extremely low latencies required for the interactive immersive XR experience are strong arguments for using THz spectrum for interactive immersive XR.

A THz link can be used for communication and/or sensing purposes (e.g. for localization or motion tracking). THz communication links for interactive immersive XR may include the following:

- Sidelink between mobile phone, local server and XR device.
- Uu between UE (XR device or mobile phone) and network.

Compared with Wi-Fi and 5G, Sidelink and Uu over THz have lower latency and higher data rate and can also support THz (RF) sensing.

A first example of interactive immersive XR is immersive XR gaming, in which the interaction is for entertainment. Existing gaming categories such as Role-Playing Games, sport games, First-Person Shooters, etc., may evolve into immersive XR gaming, but also new kinds of games may evolve. Immersive XR gaming also includes gaming in an Augmented or Mixed Reality (AR/MR), in which the experience of the physical surroundings of the gamer are augmented. Gaming may evolve beyond traditional online gaming to immersive gaming parties, such as city-wide multiplayer immersive adventure games where users can join a Gaming Party either physically or virtually, allowing personalized and enhanced user experience.

A second example of interactive immersive XR is the real-time control of remote machines, robots, vehicles, etc., in the context of applications such as flexible manufacturing and industrial automation. The XR control experience may take place in the physical environment of the remote machine by transfer of multimodal data (such as audio/visual/haptic/telemetry) to the XR user. Alternatively, the XR control experience may take place in a virtual environment that is a digital twin (i.e. virtual representation) of the remote machine and its physical surroundings.

A third example of interactive immersive XR is a distributed virtual environment for collaboration (e.g. distributed team working on a product design) This example requires a distributed virtual environment allowing interaction between multiple participants from different geographical locations over the network.

Some specific scenarios in the use case on remote education in clause 4.5 or in the use case on remote surgery in clause 4.1 may constitute further such examples.

Note that this use case focuses on the THz-based communication, sensing, etc., **at the location of the XR user**. In case of remotely controlled machines/vehicles, the communication/sensing requirements, etc., **at the location of the remote machine/vehicle** may be captured in other use cases, such as cooperative mobile robots.

4.9.2 Pre-conditions

- The XR user is under THz network coverage.
- The required wearables, sensors, etc. are properly mounted.
- The XR user is connected to the XR server.
- The XR user's identity and data are protected.

4.9.3 Service Flows

- An XR session is started.
- Sensor data, including from THz (RF) sensing, is sent from the wearables, controller, other sensors, etc., from the XR user to the server.
- The wearables, controller, sensors, etc., may communicate directly with a THz base station or via sidelink to the XR user's mobile device, which is connected to the network. The mobile device may act as a local XR server.
- In case of remote control, sensor/actuator data is sent from the remote machine/vehicle to the server and/or directly to the XR user.
- The XR server processes the received data. The server sends audio, visual, haptic, and other, data to the wearables, actuators, etc., of the XR user.
- In case of remote control, actuator data and other control information is sent to the remote machine/vehicle from the server and/or directly from the XR user's device(s).
- The actions above are repeated in real-time.
- The XR session ends.

4.9.4 Post-conditions

The XR user enjoys interactive immersive XR with audio, visual, and high sensory quality and low latency that exceeds the human senses.

4.9.5 Potential requirements

- The system should be able to provide at least 1 Gbps DL data rate and 0,1 Gbps UL data rate [i.17].
- The system should be able to provide end-to-end round-trip latency below 20 ms for at least 99 % of the time [i.17].
- The system should be able to provide reliability of at least 99,9 % [i.17].
- Distance sensing accuracy of at least 0,1 m and orientation sensing accuracy of at least 5 degrees should be supported [i.17] and [i.52].
- Translational mobility: up to 3 km/h.

- Communication service availability: The system should be able to provide a communication service availability of 99 % within the service area.
- Mobile XR media support among multiple user's devices.
- Security/Trustworthiness/user identity management and protection.

4.9.6 Physical environment

The primary physical environment for interactive immersive XR is **indoor**, for example an indoor office, a living room, etc. A secondary physical environment is a dense outdoor deployment, e.g. a courtyard, historic site, etc.

Low mobility, e.g. up to 3 km/h, can be expected in a typical indoor scenario. In addition to translational mobility of the XR user, parts of the body, such as the head, arms, and hands, are expected to move, rotate, etc.

Link distances are expected to be up to 5 m.

4.10 Use case on mission critical XR

4.10.1 Description

Mission critical XR is the XR communication for critical missions, such as public safety scenarios, and has higher service delivery priority and stricter requirements on reliability and delay compared to other XR applications, as illustrated in the example below.

Consider a scenario where a team of rescue personnel relies on mission critical XR to aid people in distress or imminent danger, as shown in figure 18 (left). Each team member wears an XR helmet, which can be either an XR device mounted on a helmet or a monolithic XR helmet. In this example, a centralized commanding vehicle acts as the control centre, receiving information from the XR helmets, and sending commands and critical data (such as the position of debris, the location of potential victims, their vital signs, etc.) to each team member via a THz link. Note that this example illustrates a centralized communication topology and assumes that the operational area has THz coverage from the commanding vehicle. If this is not the case, communication may be centralized around a squad leader. Otherwise, decentralized topologies may also be implemented. The commanding vehicle in this example also collects information using THz sensing, but other sensing sources may also be available, such as drones, surveillance cameras and audio sensors. The team members can also communicate with one another using the THz link: in cases where a team member lacks a direct radio connection to the commanding vehicle, another team member can serve as relay for communication. For example, team member 4 can relay between team member 5 and the commanding vehicle.

In an alternative scenario with a centralized communication topology, illustrated in figure 18 (right), the commanding vehicle can send rescue robots or drones to the disaster zone while the rescue team and first responders are in the commanding vehicle and are equipped with XR devices. This topology could be necessary if the disaster zone is too dangerous for the team members and to expand coverage through communication relays as explained next. The robots and drones can engage in autonomous navigation by parsing the control signals and point of view of the XR device users. The robots and drones in this scenario may also have sensing capabilities and provide additional information to the team in the control vehicle. Similar to the example above, some of the robots could serve as relays for communication.

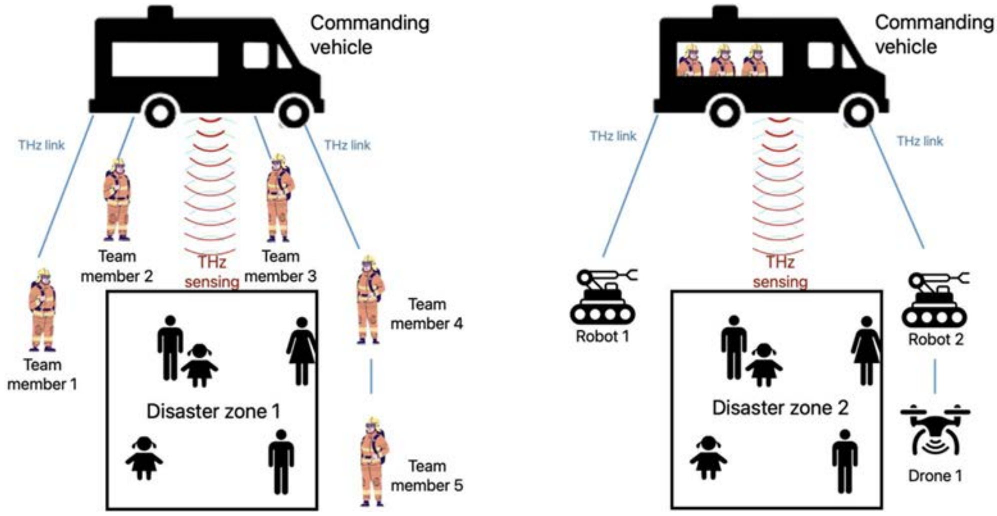

Figure 18: Mission Critical XR

4.10.2 Pre-conditions

- The THz link is reachable to at least some of the team members (or the robots/drones in high-risk scenarios).
- For scenarios with outdoor-to-indoor THz links (such as the one illustrated above), the wall of the target disaster area should be penetrated by THz signals for sensing.
- If THz-based localization and sensing is not available, the command centre (the vehicle, in the example above) can benefit from having a map of the environment and surroundings. When a map of the operation environment is not available, mission critical XR can still play an important role by enabling information exchange among the squad members.
- Besides THz sensing, additional RF and non-RF sensing capabilities are available.
- In scenarios where the environment is unsafe for the rescue team, semi-autonomous robots and drones should be available and equipped with sensors. The semi-autonomous requirement can enable seamless control by the XR-wearing squad members: the actions, gestures, and point of view of the squad members can be parsed into autonomous behaviour.

4.10.3 Service Flows

- The commanding vehicle gathers real time information of the target environment and surroundings.
- The XR helmet of each team member connects directly or over a relay device to the command centre. Otherwise, the XR headset of each member connects to the corresponding robot. The robots connect directly or over a relay device to the command centre.
- The XR helmet of each team member or robot sends real time information to the command centre, including video, audio, location, motion, vital sign status, and other sensing information.
- The commanding vehicle gathers sensed information from XR helmets, robots, and any other RF (including THz) and non-RF sensors.
- The commanding vehicle sends real time information to the XR helmet of each team member, including:
  - Commands (e.g. haptic, voice, video).
  - Victim location and status.
  - Debris location and risk information.
  - Real time map, if available.

NOTE: The above information may be sent in either unicast to an individual team member, or multicast to multiple team members or broadcast to all team members.

- The team members may also mutually communicate via XR helmets for collaboration.

4.10.4 Post-conditions

The rescue team uses mission critical XR with improved resolution and latency, and that incorporates THz-based sensing of the disaster area, to successfully complete the mission.

4.10.5 Potential requirements

- The system should support THz based mission critical XR communication, including unicast, multicast and broadcast.
- The system should support QoS mechanism for THz based mission critical XR communication.
- The system should support THz based device to device direct communication and relay for mission critical XR.

4.10.6 Physical environment

The use case works in an indoor or outdoor setting where a disaster has occurred. These areas are characterized by the presence of debris, smoke, dust, fire, heavy rain, floodings, etc. which could have an impact on the propagation of THz signals.

4.10.7 Enabling technologies

The following enabling technologies may apply:

- QoS for mission critical XR over THz link.
- Device to device direct communication and relay over THz link.
- Broadcast, multicast over THz link.
- THz based sensing and positioning.
- Semi-autonomous robotics.

4.11 Use case on real-time industrial control

4.11.1 Description

Industrial machines are equipped with one or multiple industrial computers (e.g. Programmable Logic Controllers) for the control of the manufacturing process. Computers communicate with sensors and actuators installed on the machine to monitor the status of the process and trigger actions. Similarly, sensors and actuators within a machine or across multiple machines can communicate directly among each other to exchange information relevant for decision making. Current solutions use wired fieldbus connections between sensors/actuators and industrial computers. This approach has two main disadvantages:

i) cabling increases costs, size, and weight of industrial machines;

ii) connecting sensors/actuators installed in moving parts of the machine requires special measures, e.g. reinforced cables, contact strips, etc.

In this context, wired connections can be replaced with wireless communications at THz frequencies. This solution has the potential to provide the communication performance required by industrial real-time applications without the need for cabling. In turn, it can enable a more flexible and agile management of the production line, for example by moving the control functions to a virtual controller running on an edge computing node, as illustrated in figure 19. The replacement of wired connections with wireless in the industrial setting can be seen as a use case within a broader use case on wire replacement, which may include wire replacement within vehicles, in/on the human body, etc.

Moreover, sensing capabilities of THz signals can be exploited to aid the monitoring of the industrial process and to supervise machine operations.

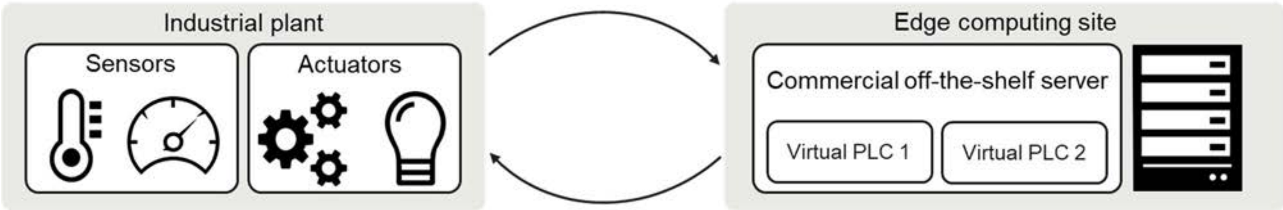

Figure 19: Real-time industrial control at the edge

4.11.2 Pre-conditions

- Industrial machine is equipped with wireless sensors and actuators.
- Industrial computer(s) is installed on the machine or in the surrounding area.
- Reliable communication link is established between:
  - i) industrial computer(s) and sensors/actuators; or
  - ii) between sensors within a machine (intra-machine) or between multiple machines (inter-machine).

4.11.3 Service Flows

The industrial computer receives data from sensors, process the received data, and triggers the actuators.

4.11.4 Post-conditions

Manufacturing process is carried out in a more efficient way.

4.11.5 Potential requirements

Potential requirements for this use case have been investigated in [i.53], [i.54], [i.16] and are reported in the following:

- Control cycles times between 200 µs and 10 ms.
- Latency below 0,1 ms.
- Reliable communications with packet reception ratio greater than 99,9999 %.
- Data rates up to 100 Mbps.
- Security and trustworthiness.

4.11.6 Physical environment

Physical environment corresponds to indoor factory, intra-machine, inter-machine communications with short and medium range.

4.11.7 Enabling Technologies

If deployed, a Reconfigurable Intelligent Surface (RIS)-based THz sensor can extract valuable information about objects, including its presence, location, shape, and material properties. In this case, a local controller computer is needed to reconfigure the THz RIS(s) and accomplish the sensing. One key advantage of THz RIS-based sensing in a factory environment lies in its high precision. By effectively controlling and shaping electromagnetic waves, an RIS can achieve high resolution in sensing, which is essential in many industrial applications, like detecting tiny defects in manufactured products or monitoring subtle changes in machine performance. This ability can be used to achieve superior performance over traditional sensing approaches. As a result, it can support large-scale sensing and provide a comprehensive view of the factory's operation.

4.12 Use case on simultaneous imaging, mapping, and localization

4.12.1 Description

In addition to communications, devices developed for the next generation of communications networks are expected to be able to sense their environment and perform imaging, mapping, and localization. For example, future AGV/UAV platoons will be widely used for automatic manufacture, delivery, detections, etc. With multiple sensors, each AGV/UAV can sense the surrounding to localize, track, and recognize the targets to be carried, delivered, or avoided. To coordinate the large number of AGVs/UAVs, base stations are required to send commands in real time. Meanwhile, the information of surroundings from multiple AGVs/UAVs can be sent back to base stations and then the environment can be reconstructed at base stations, as represented in figure 20. The map of the environment may help to improve the accuracy and efficiency of AGV/UAV sensing. Large-scale antenna arrays deployed above 100 GHz can realize high-accuracy localization and high-resolution imaging with an acceptable physical size. The computational complexity involved in the high-resolution computational imaging or localization algorithms can be alleviated by resorting to a multi-modal sensing approach, combining RF sensing with Computer Vision (CV). CV technology has demonstrated to provide good performance in problems that can be highly complex from the radio perspective, such as object detection or continuous tracking [i.55]. This suggests that CV data could aid an RF sensing application by providing information about regions of interest in the surroundings, allowing for simplified RF sensing algorithms [i.56], potentially in real-time, while also allowing for more reliable environment reconstruction algorithms through data fusion techniques [i.57].

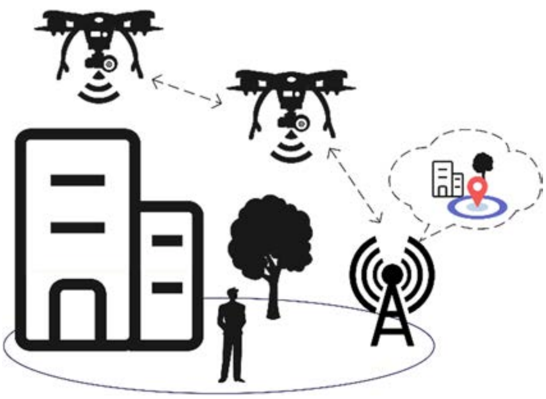

Figure 20: Simultaneous imaging, mapping, and localization

4.12.2 Pre-conditions

- Devices (e.g. AGVs/UAVs) are equipped with sensing modules.
- Devices can be controlled by a base station.
- Reliable communication link is established between devices and the base station operating as the controller.

4.12.3 Service flows

Option 1: Devices transmit THz signal, targets reflect the signal, devices receive the reflected signal, estimate the position of targets, recognize targets.

Option 2: Devices transmit THz signal, targets reflect the signal, devices receive the reflected signal, devices transmit received signal to base station, base station reconstructs the environment.

4.12.4 Post-conditions

Localizing, tracking, and recognizing targets by devices, reconstructing the environment at base stations.

4.12.5 Potential requirements

Potential requirements for this use case have been investigated in [i.58], [i.13] and are reported in the following:

- Localization accuracy relative to the distance to the detected object and its dimensions, ranging from 5 cm to 0,5 cm with confidence level of 95 %.
- Latency below 1 ms.
- Orientation accuracy below 1 degree and map reconstruction ratio of 99 %.

Orientation accuracy refers to the difference between the orientation of the actual object and the reconstructed target [i.54]. The reconstruction ratio refers to the ratio of the number of correctly reconstructed pixels to the total number of pixels.

4.12.6 Physical environment

Physical operation environment may consist of various indoor environments (meeting room, office space, classroom, living room, hallway, factory) and outdoor environments (stadium, patio, street canyon, highway, urban). Medium to high mobility is expected.

4.13 Use case on commissioning of industrial plants

4.13.1 Description

Commissioning of industrial plants or production chains is a fundamental step to ensure that all system components are working properly and fulfil the operational requirements. Modern production systems undergo to the commissioning process multiple times, as the production process needs to be constantly adapted and improved [i.59]. Typically, the integration of machine components, devices and software happens directly in the real manufacturing systems. In this case, errors in the control software or other system components can cause delays in the production and financial losses [i.60]. One special case of commissioning is the virtual commissioning of industrial plants, as described in clause 4.13.7.

4.13.2 Pre-conditions

- Industrial machine is equipped with industrial computer(s), sensors, and actuators.
- In the case of virtual commissioning of industrial plants, remote or edge server runs the simulation software hosting the digital twin; Reliable communication link is established between real devices and the simulation server.

4.13.3 Service Flows

In the case of virtual commissioning of industrial plants, the simulation software receives sensor data from the real world, updates the state variables of the digital twin and performs a simulation step. Optionally, operational commands are issued to the industrial computer.

4.13.4 Post-conditions

The commissioning process is carried out with reduced delay and costs. The production system is properly configured without delays and the manufacturing process can take place. Parameters and configuration of the production system are optimized in real time while the manufacturing process is ongoing.

4.13.5 Potential requirements

Potential requirements for maintaining a digital twin in industrial use cases have been identified in [i.61] and reported in table 4.

Table 4: KPIs for virtual commissioning of industrial plants

KPIs	Application of Digital Twin for different Use-Cases	
	Monitoring slowly varying parameters, such as temperature, etc.	Monitoring rapidly varying parameters, such as position for motion control, alarms, etc.
Availability (%)	> 99,9	99,999999
Reliability (%)	> 99,9	99,999999
Latency (ms)	100	0,1
Jitter (ms)	10	0,01
Average Throughput (Gbps)	0,01	10
Peak Throughput (Gbps)	0,01	100
Connection Density (devices/sq. m)	0,5	0,5
Safety	Critical	Critical
Integrity	Critical	Critical
Maintainability	High	High

4.13.6 Physical environment

Typical physical environment consists in indoor factory with medium range.

4.13.7 Enabling technologies

As depicted in figure 21, virtual commissioning of industrial plants relies on the use of a digital twin. Virtual commissioning makes it possible to carry out the commissioning process in a virtual replica of the real system, i.e. the digital twin, by mimicking the physical behaviour of the production process through software simulations. The simulated process on the digital twin can run simultaneously with the physical process in the real system to detect in advance possible errors in the production process, and to proactively adjust system parameters and configurations. This approach, which is often referred to as real-time co-simulation or Hardware in the Loop (HiL) validation [i.62] and [i.63], requires tight synchronization between the real system and its digital twin [i.62]. In this regard, THz communications can be exploited to enable fast and reliable communications and achieve fast feedback exchange between the production system and the simulation platform. Moreover, peculiar sensing capabilities of THz signals can aid the twinning process.

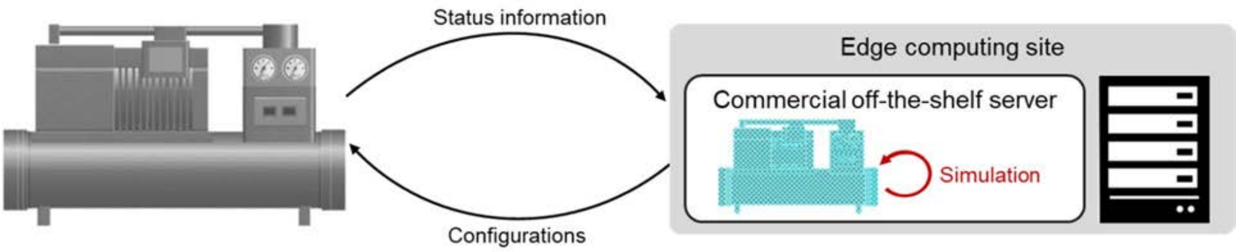

Figure 21: Virtual commissioning of industrial plants

4.14 Use case on grand events with ultra-high throughput

4.14.1 Description

Grand events can gather upwards of 100 000 people in a relatively small area (e.g. football matches, concerts, etc.). Dozens or even hundreds of ultra-high-definition cameras with 8K resolution are deployed with different viewing angles at the scene to capture dynamic images (e.g. of athletes, performers, etc.). At the same time, in order to improve the viewing experience, the on-site or online audience can use mobile phones, AR/VR and other devices simultaneously to connect to these real-time cameras to switch the viewing angle of the field to get an immersive experience and share the live stream to their friends and family, as shown in figure 22.

In this context, communication requirements relate to concurrent ultra-high throughput and ultra-high number of links in a relatively small area with low mobility. THz frequency has potential to provide an ultra-bandwidth required to support communication in such grand events.

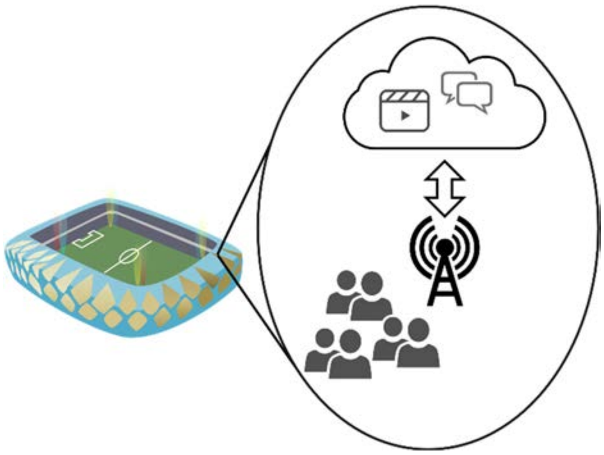

Figure 22: Grand events with ultra-high throughput

4.14.2 Pre-conditions

- Reliable low latency links are established between on-site or online users and base station(s).
- Ultra-high number of links are established between on-site or online users and base station(s).

4.14.3 Service flows

Bidirectional service stream between the local/cloud server and base stations, and between base stations and users are established.

4.14.4 Post-conditions

High throughput connections are established between users and the local/cloud server. Onsite and/or online audience can watch a ultra-high-definition video stream of the ongoing event from different viewing angles to get an immersive experience and share the live stream to their friends and family.

4.14.5 Potential requirements

- Aggregated peak rate of 1 Tbit/s per base station (e.g. 3 500 users per base station streaming ~280 Mbit/s 8K video stream).
- 2 million/km^2 device density (100 000 participants in a stadium of an area of 50 000 m^2).

- In case of two-way real-time interaction (e.g. high-definition video stream to AR glasses of onsite participants showing different angles of the grand event in real-time), low latency communication is required (e.g. lower than 1 ms as described in [i.64]).

4.14.6 Physical environment

Physical environment is characterized by outdoor environments (stadium, square), indoor stadium, low mobility, short to medium communication range.

4.15 Use case on ultra-high throughput for indoor users

4.15.1 Description

6G is foreseen to support ultra-high throughput for indoor users to enable data-hungry applications, such as streaming, multimedia services, or downloading of extremely large files. There are two typical scenarios for indoor users. The first one is for a personal network, e.g. living room or bedroom; and the second one is for public area, e.g. open office, shopping mall, or airport. The indoor users are usually static or with low mobility.

There are two categories of wireless technologies that enable the services for indoor users: Wi-Fi and cellular technologies. They both have their advantages and disadvantages. The present document considers cellular technologies. Even though cellular technologies can support high-rank Multiple-Input Multiple-Out (MIMO) transmissions to fulfil the demanding data rate requirements, in practice the number of deployed antennas at a user equipment (e.g. mobile phone, smart watch, etc.) is limited due to the form factor constraint, which poses hurdles towards realizing the potential high-rank MIMO gain. In this regard, the large available spectrum at THz bands can be utilized to compensate for the limited transmission rank due to the UE form factor constraint.

One major challenge towards exploiting outdoor THz base stations for indoor users is the deep penetration. Specifically, in addition to the severe propagation conditions at such high frequency bands, the link quality is further degraded significantly due to the Outdoor-to-Indoor (O2I) penetration loss. This is a key learning from 5G NR millimetre-wave deployments. Hence, indoor deployment of communication nodes is crucial to support ultra-high throughput for indoor users.

An illustration of the communications for indoor users is illustrated in figure 23.

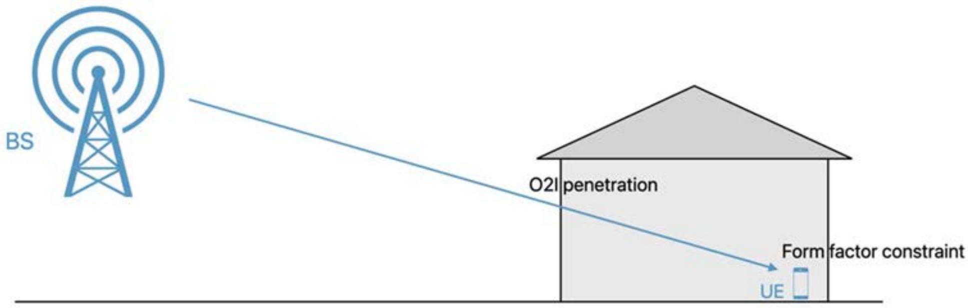

Figure 23: Outdoor-to-indoor wireless communications for an indoor user

The inside station scenario for the railway is also a use case with ultra-high throughput for indoor users [i.10]. Railway communications will be required to evolve to support various high-data-rate applications (e.g. [i.6] and [i.7]): **Real-time-train dispatching High Definition (HD) video** between trains and Train Control Centres (TCCs) is required for train dispatching and driverless systems, as well as **Journey information** that dynamically updates journey information for all passengers via multimedia.

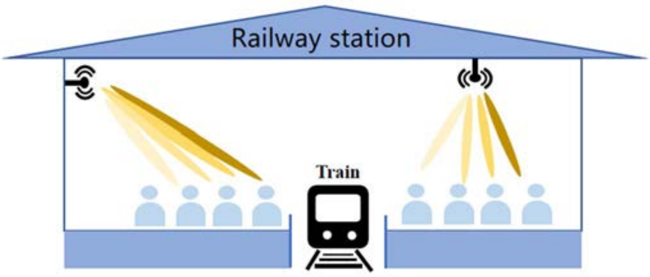

Figure 24: Inside station scenario

Figure 24 illustrates the inside station scenario: Inside station (links between Access Points (APs) and UEs in train/metro stations), where users are strongly interested to get access to mobile broadband applications (e.g. 1 Gbps, for indoor user [i.8]), and the station will provide a fixed/wireless communication infrastructure to support general commercial as well as operational applications.

4.15.2 Pre-conditions

A static or low-mobility indoor UE requires ultra-high throughput services.

A communication node is used to serve the indoor UE. This is illustrated in figure 25. There are multiple alternatives of the communication node, e.g. AP, Customer Premise Equipment, or other newly introduced entities. The backhaul link, i.e. the link between the network and the communication node, can use different technologies, e.g. optical or wireless communication.

The THz link between the communication node and the indoor UE utilizes the wide THz bands for boosting data rate. This requires that the indoor UE is under THz coverage and supports the connection and communication with the communication node.

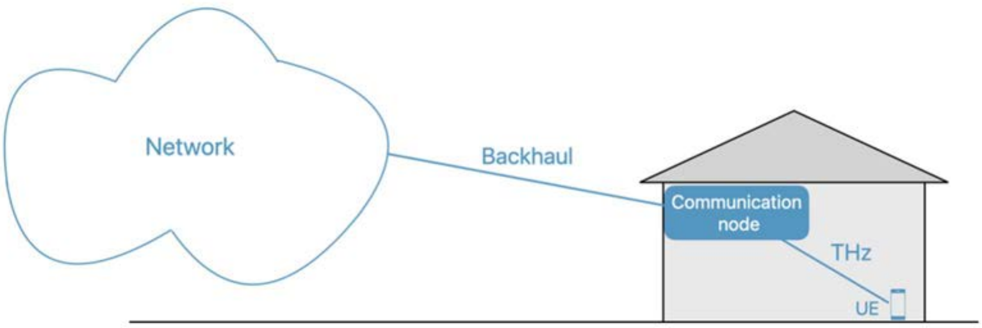

Figure 25: Indoor THz link between communication node and UE

4.15.3 Service Flows

For the DownLink (DL) direction, when an indoor UE is running an application requiring ultra-high throughput, the following service flow is required:

- The indoor UE discovers and connects to a communication node.
- The communication node receives data from the network via a backhaul link.
- The communication node transmits the received data to the indoor UE via a THz link.
- The indoor UE disconnects with the communication node when the application ends.

Similarly, for the UpLink (UL) direction, when an indoor UE is running an application requiring ultra-high throughput, the below service flow is required:

- The indoor UE discovers and connects to a communication node.

- The communication node receives data from the indoor UE via THz link.
- The communication node forwards the received data to the network via a backhaul link.
- The indoor UE disconnects with the communication node when the application ends.

4.15.4 Post-conditions

Indoor UE enjoys ultra-high throughput services via the communication node. More specifically, both benefits of lower frequency bands (e.g. better link propagation quality) and THz link (wide spectrum) can be enjoyed. Moreover, higher-rank transmission can potentially be achieved even if the end user has limited form factor constraint.

4.15.5 Potential requirements

Applications envisioned for this use case, such as holographic telepresence, will require data rates in the order of Tbps [i.28] and [i.44]. In several indoor scenarios, such as inside a station, many UEs need to be concurrently served.

For the inside station scenario, the use case will work in the "Smart rail mobility" environments [i.10]. The following KPIs from [i.8] also apply:

- Very dense crowds of users (up to 10^6 devices/km^2).
- Very low latency (down to 1 ms).
- Up to 1 Gbps throughput [i.10].

4.15.6 Physical environment

Various indoor environments (meeting room, office space, classroom, living room, hallway, factory, train station, etc.), low mobility, short to medium range.

4.15.7 Enabling technologies

Out-Of-Band L1 relay

Among the alternatives of the communication node, Out-Of-Band (OOB) Layer 1 (L1) relay is introduced as a promising enabling technology to assist the ultra-high data rate transmission for an indoor user, as shown in figure 26.

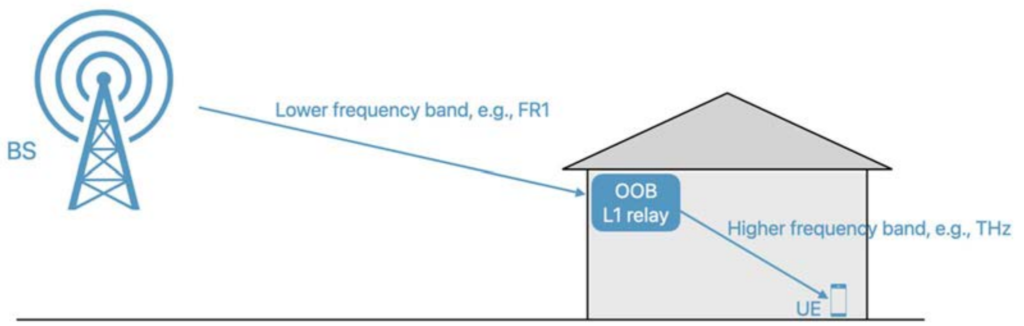

Figure 26: OOB L1 relay assisted transmission for indoor user

OOB L1 relay is typically installed inside a building. It has a much more relaxed form factor constraint compared to a normal indoor UE in terms of e.g. a larger number of antennas. Moreover, OOB L1 relay has the capability to receive data at one frequency, process and further transmit the data at another frequency.

With OOB L1 relay, the data plane is terminated at the physical layer of a relay node, where the two hops are operated on different frequency bands and can use the same or different Radio Access Technologies (RATs). In this way, together with the relaxed form factor constraint of the relay, the benefits of the low/mid bands, i.e. better propagation conditions to support higher rank transmission, and THz bands, i.e. wide spectrum, can be jointly realized.

For example, in DL direction, OOB L1 relay first receives high-rank MIMO transmission from BS at low/mid band. Then, OOB L1 relay translates the received low/mid band signal into the signal for THz band. Finally, OOB L1 relay sends the translated signal to UE via THz band.

Besides OOB L1 relay, distributed cloud or local cloud compute is an evolving technology that depends on high bandwidth links to enable low latency requirements of compute data transmission between the distributed devices. Local compute offload from a high compute requirement, such as an XR device, can be offloaded to other devices in indoor environments.

Transmissive reconfigurable intelligent surfaces

The Transmissive Reconfigurable Intelligent Surface (T-RIS) represents a promising enabling technology to assist the ultra-high data rate transmission from the outdoor BS to an indoor UE. In particular, the T-RIS technology can be used to transmit the THz electromagnetic waves from O2I (T-RIS L1) and vice versa, and to generate an ultra-high throughput access point (T-RIS L2), as shown in figure 27, adapted from [i.21].

The T-RIS L1 can be a passive (one or multiple fixed beams) or a reconfigurable transmissive RIS acting as an electromagnetic wave repeater. Thanks to a fixed bidirectional directive pattern, the electromagnetic wave repeater can regenerate passively (without power consumption) the THz signal in indoor or outdoor from/to a backhauling to/from an indoor hotspot. When multiple outdoor backhauling links and/or indoor hotspots need to be interconnected, reconfigurable T-RISs can be used to implement the repeater at the cost of power consumption to control electronically the beam directions. In this case, a specific beam management algorithm should be implemented. The beam management can be supervised by an additional radio-frequency system operating at lower frequency and collecting the beam direction requirements.

In order to handle the indoor signals, the T-RIS L2 is integrated at hotspot level to connect one or several UE terminals operating at THz. In this frequency range, the use of a T-RIS with electronically steering capability (single or multi beams) represents a promising enabling technology if compared to classical phased array antennas. In contrast with phased arrays, the spatial feeding technology of a T-RIS integrated with a THz transceiver with a focal array can drastically limit the power division loss when an array with several thousands of elements is required to generate a certain gain. Furthermore, the use of radio-frequency switches integrated into the T-RIS aperture drastically limits the insertion loss, the complexity, and the power consumption of the phase control mechanism required to electronically steer the beam.

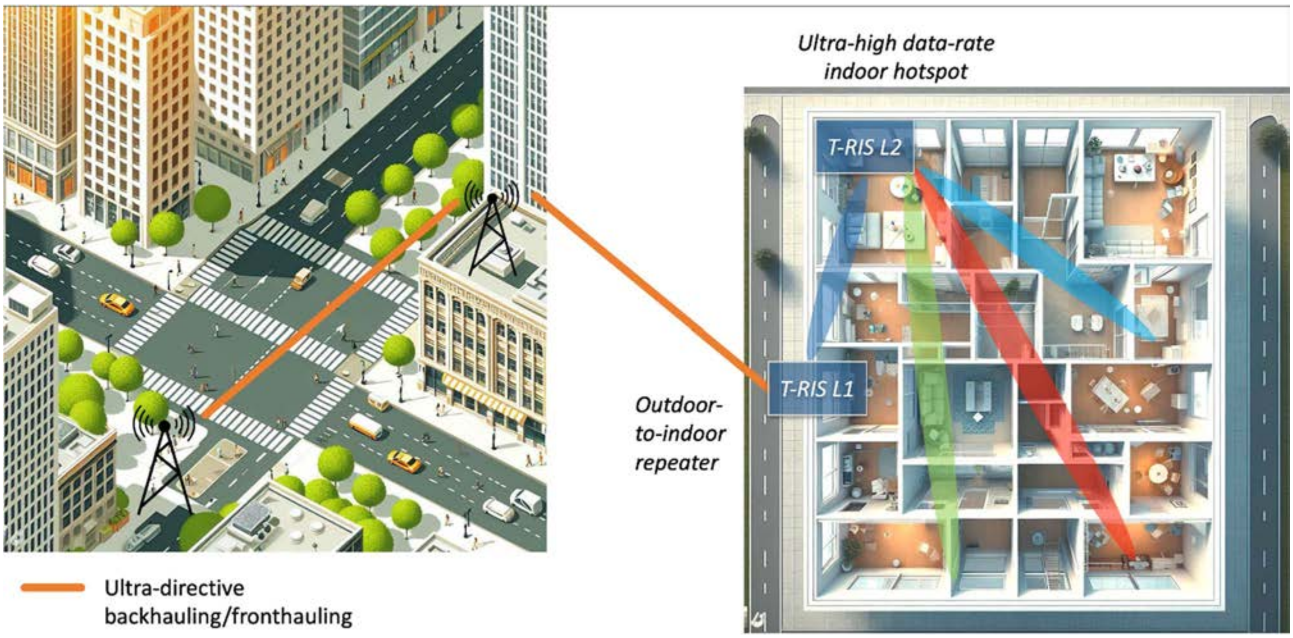

Figure 27: Use case on Ultra-high throughput for indoor users

4.16 Use case on intra-device communications

4.16.1 Description

Intra-device communication is a communication link within a small, medium or large device. A small device includes inter-chip communication to allow for pin count reduction. A medium device includes for example board to board communication with a computer, camera or video projector. Some technologies for medium devices are already available solving the copper issue like Light Peak fibre technology. Light Peak is a high-speed optical cable technology designed to connect electronic devices to each other. Light Peak delivers high bandwidth starting at 10 Gbps and up to 40 Gbps. It uses Peripheral Component Interconnect Express (PCI Express) or Display Port protocols. Indeed, one main issue is the need to use connectors on the boards which increase the cost and their design complexity. Another issue, which is obvious, is the cable which limits the flexibility when connecting the boards. THz can provide the corresponding data rates omitting the use of cables. Large device are for example machines, e.g. milling machines.

4.16.2 Pre-conditions

THz transmitter and receiver are mounted inside device (e.g. camera, video projector, computer or milling machine).

4.16.3 Service Flows

- The intra-device connection is set-up and configured during the start-up phase of the device.
- The intra-device connection is shut-down during the shut-down phase of the device.

4.16.4 Post-conditions

Cabling for ultra-high data rate connections can be replaced by THz wireless links, thus allowing an easier reconfiguration of a device and mitigating electromagnetic compatibility problems by controlled radiation between two directive antennas.

4.16.5 Potential requirements

Table 5.1 in [i.45] provides a list of required data rates needed to transmit common video formats, for example between a liquid crystal display and a storage device in a video projector. The Bit Error Rate should be less that 10^{-12} after Forward Error Correction and corresponds to one error every 10 s at 100 Gbps.

4.16.6 Physical environment

Intra-device connections are static with fixed point-tp-point connections. The conditions of the static radio environment, e.g. the channel estimation, can be determined during the start-up of the device.

4.17 Use case on local area collaboration for fixed or low mobility applications

4.17.1 Description

4.17.1.1 Introduction

Local area collaboration refers to device cooperation based on local communication involving 2 or more devices that interact to enable transfer of user data, unified control procedures, cellular control procedure or processing offloading as well as application related compute offloading. Device cooperation can involve various device types, for example smartphones, watches, glasses, notebooks, tablets or Internet of Things (IoT) devices. Cooperating devices may belong to a single user but might also be owned by multiple users, for example a family.

It is assumed that cooperating devices are located close to each other connected via Device-to-Device (D2D) links. This clause describes use cases that justify THz links for the purpose of D2D communication. THz links allow super high-performance communication in short range and enable many use cases for local collaboration among devices.

4.17.1.2 Fast local media and file sharing

Local media and file sharing is a very popular use case between mobile devices as well as between mobile and stationary devices. Users expect to be able to transfer large amounts of data seamlessly between devices in short time, as depicted in figure 28. THz links can enable super high-speed media and file sharing between cooperating devices.

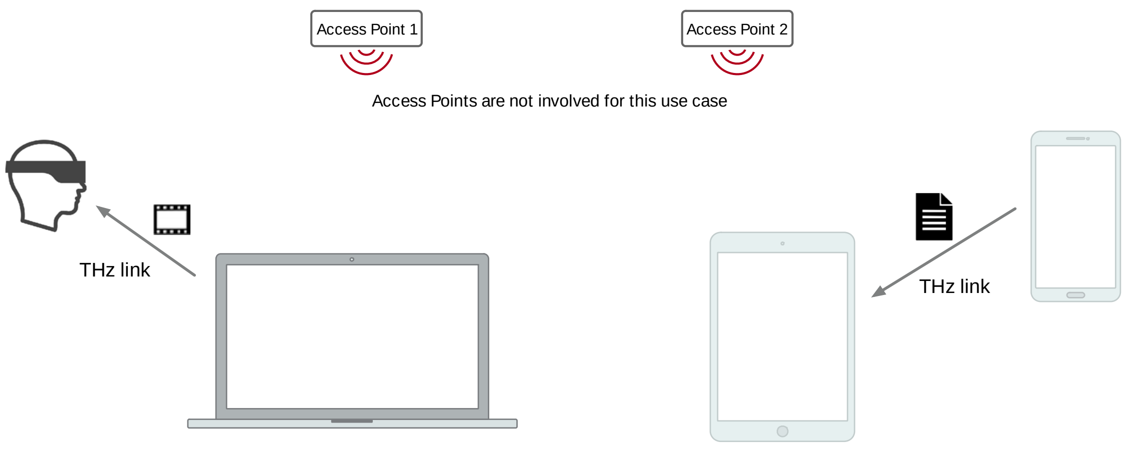

Figure 28: Fast local media and file sharing

4.17.1.3 High-speed wireless data backup

Backup of data to a close by storage is another important use case. The storage could be a local hard drive or a user, company, or family local cloud server. THz links can enable fast backing up of data once the user comes in proximity to the storage device without the need to connect a USB stick or even a cable.

Local area collaboration also enables backup of data transferring the data via relay devices within the local collaboration group. Figure 29 illustrates an example involving 3 mobile devices and 1 storage device. Device 1 is a laptop/notebook device that performs a backup in the storage device by transferring a large amount of data. Device 2 is a tablet device that backs up its own data and, in addition, serves as a relay for Device 3. Device 3 is a smartphone which requires to backup pictures or video. As Device 3 is not in direct THz coverage of the Storage Device, Devices 2 and 3 cooperate and Device 3 utilizes Device 2 as a relay. Device 2 then forwards the data of Device 3 to the Storage Device.

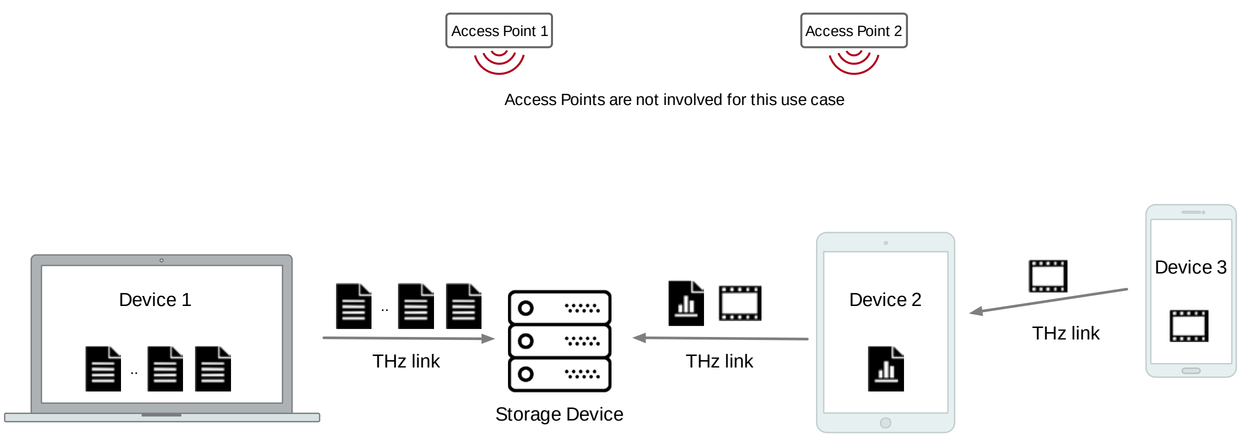

Figure 29: High-speed wireless data backup

4.17.1.4 Device centric mesh sub-network and UE collaboration

Based on local area communication, devices can form a device centric local mesh sub-network. Multi-hop relay inside the mesh sub-networks can extend range and coverage of cellular communication. The devices in the mesh sub-network may also collaboratively communicate with cellular network for better performance, e.g. as in a virtual UE, illustrated in figure 30. Collaboration across the devices for transferring data from and to the network can increase user data throughput by aggregating resources and can increase reliability by applying redundant communication across devices.

The Uu communication can also be offloaded to D2D direct communication to save Uu power and Uu resources. Device power consumption will benefit due to utilizing short range communication.

The device centric mesh sub-network may be a personal or company network consisting of THz links between wearables, smartphones, tablets, notebooks/laptops, IoT-devices and other mobile devices.

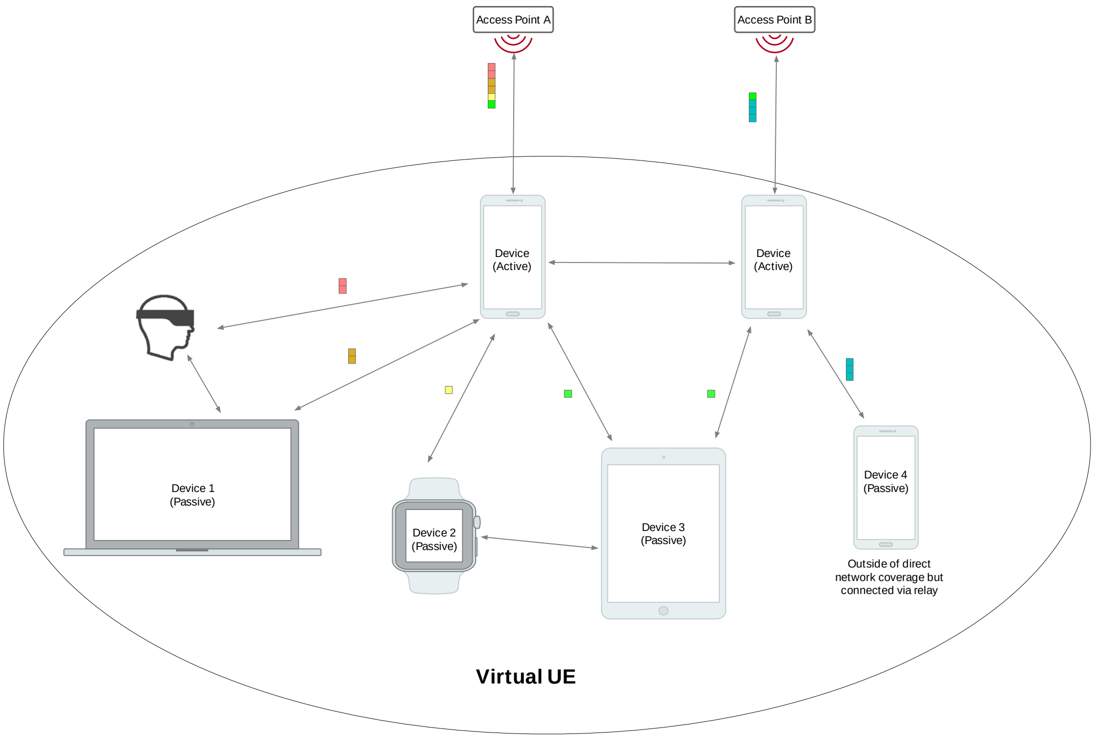

Figure 30: UE Local Cooperation

4.17.1.5 Local compute offloading

Various device types, such as wearables, glasses and IoT devices, have limited compute capabilities due to size and/or power consumption constraints. This requires offloading compute efforts to nearby devices that own higher compute capabilities, as depicted in figure 31. THz links can enable compute offloading via reliable and low latency short range communication.

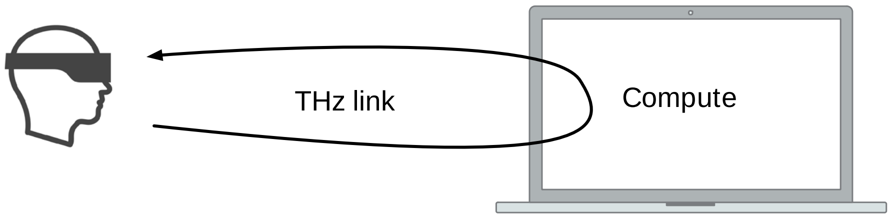

Figure 31: Local Compute Offloading

4.17.2 Pre-conditions

A UE supporting THz is in range of local THz wireless communication and able to discover the presence of UEs able to cooperate locally.

4.17.3 Service flows

In cellular Base Station (BS) coverage the BS may configure the UE-UE THz direct discovery and communication. Outside of cellular coverage, devices autonomously discover presence of a local collaboration group and communicate using (pre-)configured THz resource. For both cases, the below service flow is required:

- UEs with THz capabilities moves into proximity of a local collaboration device or group.
- UEs establish a D2D THz link to the nearby device(s) and enter a local collaboration group.
- THz link is used for local collaboration to transfer user and control related information.

4.17.4 Post-conditions

Two or more devices have established a collaboration group and interact based on UE-UE direct THz links with less power consumption, higher spectrum efficiency, shorter delay and higher throughput.

4.17.5 Potential requirements

- The system should support Local Area Collaboration utilizing device to device THz radio links.
- The system should support BS-controlled UE-UE direct discovery and communication over THz band.
- The system should support UE autonomous direct discovery and communication over THz band.
- The system should support offloading Uu communication to UE-UE direct communication over THz band.
- The system should support dynamic switching between Uu and THz UE-UE direct communication.
- The system should support UE-UE collaboration for high performance Uu communication.
- The system should support UE-UE direct discovery and communication over unlicensed THz band.
- The system should support directional listen-before-talk and/or directional listen-before-receive shared spectrum access.

4.17.6 Physical environment

These use cases work indoor as well as outdoor under the condition that UEs are mutually reachable via THz links in a local area. The use cases also work under mobility scenarios where a set of UEs is travelling jointly.

4.18 Use case on local area collaboration for vehicular applications

4.18.1 Description

4.18.1.0 General overview

Collaboration with high-speed mobility mainly refers to the cooperation between communication nodes that are in a mobile scenario. It is important to guarantee low latency and high reliability of communication in this scenario based on THz links. This clause mainly describes two typical use cases for application scenarios with high-speed mobility: vehicle-to-everything and train-to-train scenarios.

4.18.1.1 Local area collaboration for V2X (Vehicle-to-everything)

Low latency and ultra-high reliable communication are essential for V2X applications. THz spectrum can be used for V2X scenarios to enable high performance communication and accurate sensing.

The local collaboration requires UE-UE discovery and direct communication. In cellular coverage, direct communication and discovery over THz band may be configured and controlled by BS. Outside of cellular coverage, devices can autonomously discover and communicate over (pre-)configured THz resources.

Figure 32 provides example use cases for Vehicle-to-Vehicle (V2V) and V2X communication:

- Base station BS1 configures and controls the THz direct communication link between the pickup truck and the car.
- Base station BS2 configures and controls the THz direct communication link between the car and a roadside unit, e.g. a traffic light.
- The direct THz communication link between the pickup truck and the car is established based on direct discovery between the vehicles not involving any base station.

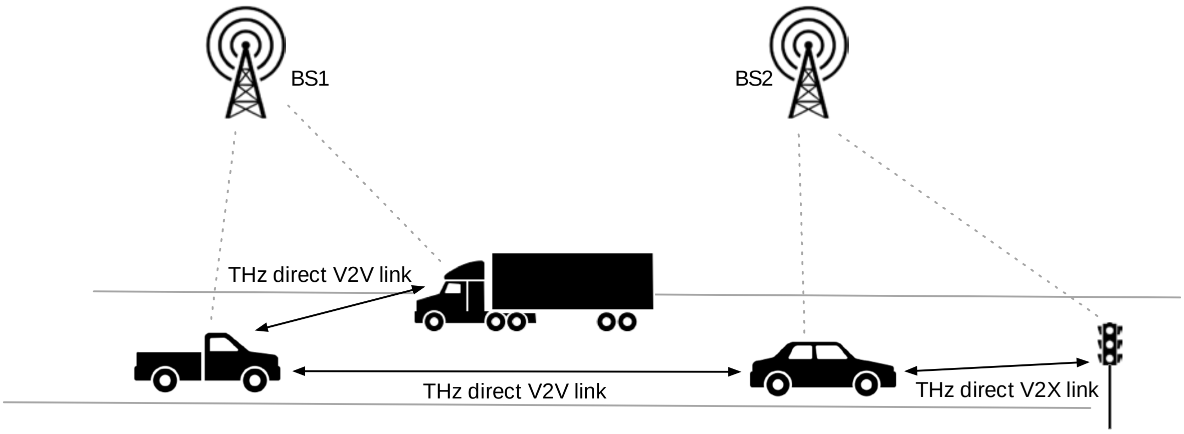

Figure 32: V2V and V2X local collaboration

Local collaboration allows to offload the Uu based communication between vehicles, flowing via BS and core network (orange line in figure 33), to direct V2V communication. When the distance between the vehicles enters the range of THz coverage the direct communication (green line in figure 33) between vehicles is established as shown in figure 33.

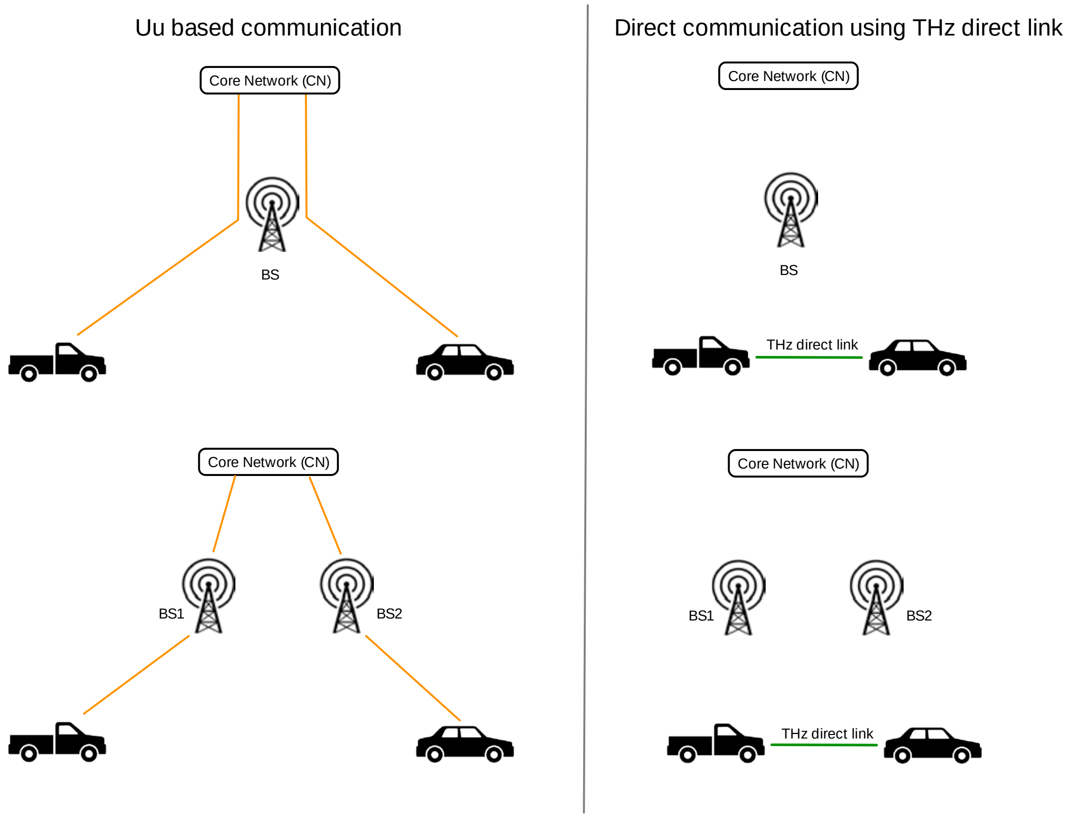

Figure 33: Offloading Uu communication (same BS or Different BS) to V2X direct communications

4.18.1.2 Local area collaboration for train-to-train scenarios

Train-to-Train (T2T) scenario is a typical railways use case for collaboration for vehicular applications [i.10]. In the future, railway communications are required to evolve to various high-data-rate applications (e.g. [i.6] and [i.7]). Examples of such applications include:

- **On-board real-time high-data rate connectivity** for web browsing, video conferencing, video broadcast, etc.
- **Train operation information** that provides critical information regarding voice and control signaling, on-route train performance, and train equipment status.
- **Journey information** that dynamically updates journey information for all passengers via multimedia.

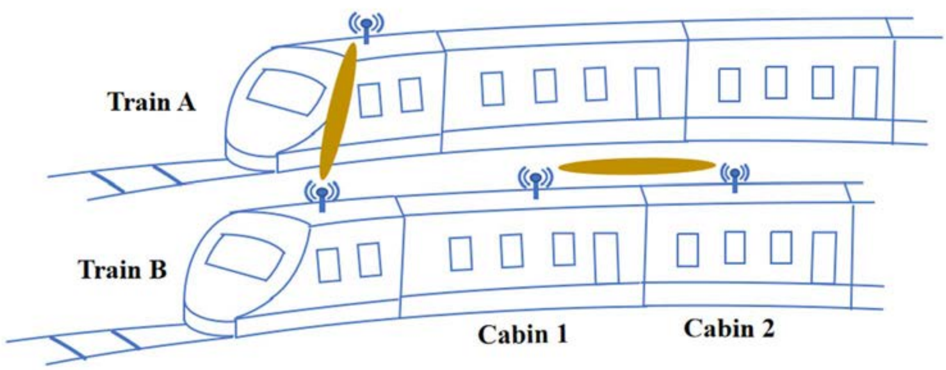

Figure 34: Train-to-train scenario

Figure 34 illustrates the T2T communication scenario. It mainly focuses on two cases:

i) a communication link between two trains that are close to each other; and

ii) a communication link between Access Points (APs) in different cabins of the same train.

The APs are mounted on the top of the cabins (outside), which indicates that the channel between them is line-of-sight.

T2T requires a high-data rate and a low latency because the APs are arranged in every cabin such that each AP serves as a client station for the APs in the other cabins, while also serving as an AP for all the stations within its cabin [i.65]. So, this scenario requires two or more times (depending on how many train cabins are connected) of bandwidth with respect to the "In-train cabin" scenario.

4.18.2 Pre-conditions

A UE supporting THz is in range of local THz wireless communication and able to discover the presence of UEs able to cooperate locally.

For railway T2T scenarios, the on-board infrastructure, train cabin, and mobile users inside the cabin are able to connect to the network through a THz link.

4.18.3 Service flows

In cellular BS coverage, the BS may configure the UE-UE THz direct discovery and communication. Outside of cellular coverage, devices autonomously discover presence of a local collaboration group and communicate using (pre-)configured THz resource.

4.18.4 Post-conditions

Based on direct THz links, V2X or T2T establish communication with less power consumption, higher spectrum efficiency, shorter delay, and higher throughput. It will also enable to fulfil the requirement of microsecond latency in the ETCS level-3 for the communications between trains and the Train Control Centre (TCC).

4.18.5 Potential requirements

- The system should support dynamic switching between Uu and THz UE-UE direct communication.
- The system should support UE-UE collaboration for high performance Uu communication.
- The system should support UE-UE direct discovery and communication over unlicensed THz band.

The following KPIs from [i.8] also apply to the T2T scenario:

- Very high data rate (peak data rate - up to 20 Gbit/s, user experienced data rate - up to 100 Mbit/s).
- Very dense crowds of users (up to 10^6 devices/km^2).
- Very low latency (down to 1 ms).

4.18.6 Physical environment

For railway T2T scenario, the use case will work in the "Smart rail mobility" environments [i.10].

4.19 Use case on predictive maintenance and diagnostics

4.19.1 Description

Proper maintenance and fault diagnostics are crucial operations to avoid unplanned interruptions and ensure seamless functioning of industrial machines and manufacturing systems. With the advent of Industry 4.0, predictive maintenance and predictive diagnostics have been introduced to improve the efficiency of these operations [i.66], like depicted in figure 35. These solutions collect data from sensors installed in the production system and make use of data analytics tools to monitor the status of the machine, possibly exploiting a digital twin [i.61]. The results are then used to properly schedule regular maintenance cycles, discover potential faults, and trigger extraordinary maintenance operations. This approach can improve the efficiency of the production system and avoid unplanned interruptions.

Typically, predictive maintenance and diagnostics systems make use of an edge computing infrastructure which communicates with one or multiple industrial machines to collect the sensor data and executes the analytics algorithms. In this regard, THz communications can realize the data connection between the industrial machine and the edge computer.

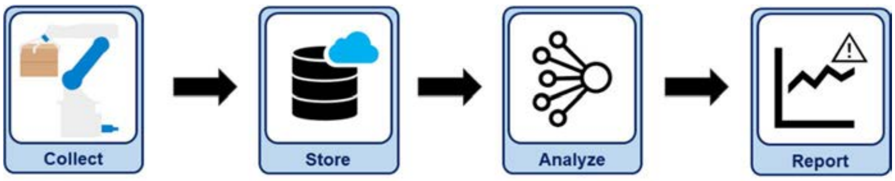

Figure 35: Predictive maintenance and diagnostics

4.19.2 Pre-conditions

- One or multiple industrial machines equipped with multiple sensors.
- Edge computing node communicating with industrial machines.

4.19.3 Service Flows

Edge computing node collects sensor data, executes data analytics algorithms, and produces a report with maintenance and diagnostics.

4.19.4 Post-conditions

Regular maintenance cycles are properly scheduled, potential faults are discovered.

4.19.5 Potential requirements

High data rate to collect a large volume of data from devices deployed in the field is required. Number and type of devices depend on the specific application. For example, large industrial machine (e.g. paper machines) could integrate hundreds of devices, including sensors, drivers, and vision systems (e.g. cameras). The rate with which devices generate data typically depends on the control cycle duration, which is related to process dynamics, e.g. highly dynamic processes may have sub-milliseconds control cycles. In turn, this has an impact on the data rate required to upload the collected data to the edge computer.

Potential requirements for digital-twin-related data transmission for offline processing purposes (e.g. running predictive maintenance algorithms) have been identified in [i.61] and reported in table 6.

Table 6: KPI requirements for digital twin-related data transmission

Availability (%)	99,9
Reliability (%)	99,9
Average Throughput (Gbps)	10
Peak Throughput (Gbps)	100
Connection Density (devices/sq. m)	0,5
Safety	Low
Integrity	High
Maintainability	Low

4.19.6 Physical environment

Indoor factory.

5 Considerations

5.1 Mapping the identified use cases and deployment scenarios to relevant channel measurements scenarios

In order to support the evaluation of the use cases defined in clause 4 through simulations, one necessary component is the definition of channel models for THz communications and sensing in the environments where the use case will be deployed. To that end, each use case described in clause 4 contains the description of the target physical environment. Table 7 below summarizes each of the physical environments, classifies them into two groups (indoor and outdoor), and indicates related THz channel measurement studies available in the existing literature for that particular environment. Furthermore, within the scope of ETSI GR THz 003 [i.67] deals with channel measurements and modelling for THz bands and will aim to provide channel measurements and models for the physical environments identified in table 7. In addition, other typical indoor environments as specified in Recommendation ITU-R 1238 [i.68], such as conference room, corridors, railway stations, airport terminals and commercial environments and outdoor environments as specified in Recommendation ITU-R 1411 [i.69], including residential, urban and suburban will be considered for typical deployment scenarios.

Table 7: Mapping the identified use cases and deployment scenarios to relevant channel measurements scenarios

Physical environment / Use case	Indoor													Outdoor					
	On-body	Medical facility	Living room	Airplane cabin	Train cabin	Factory	Classroom	Data centre	Hallway	Meeting room	Office	Intra-machine/ device	Inter-machine	Open space	Highway	Urban street	Urban canyon	Stadium	Square
Remote surgery	Y	Y	Y																
In-airplane / train cabin entertainment				Y	Y														
Cooperative mobile robots						Y													
Hazardous material work						Y													
Remote education							Y												
Fixed wireless X-haul transport														Y	Y	Y	Y	Y	Y
Mobile wireless X-haul transport														Y	Y	Y	Y		
Wireless data centres								Y											
Interactive immersive XR			Y								Y								
Mission critical XR		Y	Y			Y	Y	Y			Y			Y		Y	Y	Y	Y
Real-time industrial control						Y						Y	Y						
Simultaneous imaging, mapping, and localization			Y				Y		Y	Y	Y							Y	Y
Commissioning of industrial plants						Y													
Grand Events with Ultra-High Throughput																		Y	Y
Ultra-high throughput for indoor users			Y				Y		Y	Y	Y								
Intra-device communications												Y							
Local area collaboration for fixed/low mobility applications	Y	Y	Y			Y	Y		Y	Y	Y			Y				Y	Y
Local area collaboration with mobility														Y	Y	Y	Y		
Predictive maintenance and diagnostics						Y													

Physical environment / Use case	Indoor													Outdoor					
	On-body	Medical facility	Living room	Airplane cabin	Train cabin	Factory	Classroom	Data centre	Hallway	Meeting room	Office	Intra-machine/device	Inter-machine	Open space	Highway	Urban street	Urban canyon	Stadium	Square
Related measurement study				[i.99] [i.133] [i.136]	[i.99] [i.102] [i.106] [i.107] [i.131]	[i.126]	[i.131]	[i.93] [i.94] [i.95] [i.96] [i.111] [i.112] [i.113] [i.131]	[i.72] [i.119] [i.120] [i.123] [i.131]	[i.71] [i.73] [i.98] [i.101] [i.105] [i.114] [i.115] [i.116] [i.130] [i.131] [i.136] [i.137]	[i.74] [i.76] [i.83] [i.89] [i.117] [i.118] [i.125]	[i.77] [i.79] [i.81] [i.82] [i.84] [i.88] [i.93] [i.100] [i.134] [i.136]	[i.138]	[i.90] [i.91] [i.92] [i.109] [i.131]	[i.97] [i.104] [i.127] [i.128] [i.129] [i.132]	[i.109] [i.121] [i.122] [i.124] [i.127] [i.128] [i.129] [i.131]	[i.109] [i.121] [i.122] [i.124] [i.131]		
NOTE: The following generic references apply to all use cases: [i.70], [i.75], [i.78], [i.80], [i.85], [i.86], [i.87], [i.103], [i.108], [i.110] and [i.136].																			

5.2 General considerations on use case characterization

5.2.1 Considerations on mobility of wireless terminals

The identified use cases can be categorized based on the mobility of wireless nodes. A first group includes the use cases with fixed nodes, such as:

- the use cases on intra-device communications (clause 4.16), wireless data centres (clause 4.8), and wireless fixed point to (multi)point transmission (e.g. X-haul transport, enterprise point-to-point) (clause 4.6), which have the purpose of replacing wired connections with high-capacity THz links;
- the use cases on remote real-time control of industrial machines (clause 4.11), commissioning of industrial plants (clause 4.13), and predictive maintenance and diagnostics (clause 4.19) which are targeting industrial applications.

Another group of use cases is characterized by limited mobility, such as:

- the use case on in-airplane or in-train cabin entertainment described in clause 4.2 where THz communications are used to provide connectivity to passengers sitting on a plane or train; and
- the use case on local area collaboration for fixed or low mobility applications (clause 4.17) where THz wireless links are established between wearables, smartphones, tablets, and other personal devices.

A third group includes use cases with mobile nodes, such as:

- the use cases on cooperative mobile robots (clause 4.3), hazardous material work (clause 4.4), remote surgery (clause 4.1), and simultaneous imaging, mapping, and localization (clause 4.12) which involve mobile robots and drones;
- the use cases on grand events with ultra-high throughput (clause 4.14) and ultra-high throughput for indoor users (clause 4.15) where THz connectivity provides access to mobile users;
- the use cases on local area collaboration for vehicular applications (clause 4.18) and mobile wireless X-haul transport (clause 4.7) where THz wireless links are established between moving vehicles;
- the use cases on interactive and immersive XR (clause 4.9), mission critical XR (clause 4.10), and remote education (clause 4.5) which are dealing with users wearing wireless XR headsets.

The use cases belonging to the first and second groups are characterized by no (or very limited) mobility, thus not requiring complex link management operations. On the other hand, establishing and maintaining wireless links when the end nodes are moving is a complex task, especially when the communication range is limited, and directional antennas are adopted. In this regard, applications included in the third group may require more advanced procedure for establishing and maintaining wireless connections when the end nodes are moving.

This is summarized in table 8.

Table 8: Relationship between use cases and mobility categories

Mobility category / Use case	Fixed wireless nodes	Wireless nodes with limited mobility	Mobile wireless nodes
Remote surgery			X
In-airplane / train cabin entertainment		X	
Cooperative mobile robots			X
Hazardous material work			X
Remote education			X
Fixed wireless X-haul transport	X		
Mobile wireless X-haul transport			X
Wireless data centres	X		
Interactive immersive XR			X
Mission critical XR			X
Real-time industrial control	X		
Simultaneous imaging, mapping, and localization			X
Commissioning of industrial plants	X		
Grand Events with Ultra-High Throughput			X
Ultra-high throughput for indoor users			X
Intra-device communications	X		
Local area collaboration for fixed/low mobility applications		X	
Local area collaboration with mobility			X
Predictive maintenance and diagnostics	X		

5.2.2 Considerations on sensing functionalities

Thanks to their peculiar propagation characteristics, THz bands can be exploited not only for communications, but also for sensing, imaging, and localization purposes.

In this regard, the first group covers the use cases that could benefit from enhanced sensing functionalities able to characterize the physical properties of objects, for example to determine their material composition or detect the presence of certain substances. Applications belonging to this group include:

- the use case on hazardous material work (clause 4.4) where THz sensing features could be used to detect the presence of harmful substances;
- the use case on remote education (clause 4.5) where remote participants may benefit from an enhanced learning experience when sensing is available.

In the second group, use cases may take advantage of THz imaging capabilities, for example:

- the use case on remote surgery (clause 4.1) where THz biomedical imaging could assist the surgeon;
- the use case on hazardous material work (clause 4.4) to detect the presence of hidden objects;
- the use case on simultaneous imaging, localization, and mapping (clause 4.12) to enhance the context awareness and improve the perception of the surroundings;
- the use case on predictive maintenance and diagnostics (clause 4.19) to detect structural faults in products or industrial machineries through non-destructive testing techniques.

The third group includes use cases for which enhanced localization and ranging functionalities may play a role, such as:

- the use cases on cooperative mobile robots (clause 4.3) and simultaneous imaging, localization, and mapping (clause 4.12) where precise localization functionalities can assist robots and drones operations;
- the use cases on interactive and immersive XR (clause 4.9) and mission critical XR (clause 4.10) where localization is used to enhance the experience of XR users;
- the use case on real time industrial control (clause 4.11) where localization of industrial devices can aid the monitoring of the industrial process and supervise machine operations.

5.3 Considerations on related application areas

Recent considerations on the technical evolution tend to shift the focus from previous generations of technologies concentrating on network performance to a societal value-driven approach to technology development in 6G [i.140] and [i.139]. Moreover, the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, defined 17 Sustainable Development Goals (SDG) [i.141] some of which could be supported by technology developments in the 6G framework such as:

- Technology related goals such as industry, innovation, and infrastructure (SDG#9), responsible consumption and production (SDG#12).
- Environmental awareness goals such as sustainable cities and communities (SDG#11) or climate action (SDG#13).
- Quality of life goals such as good health and well-being (SDG#3), quality education (SDG#4), decent work and economic growth (SDG#8).

6G use cases described in the present report and enabled by THz communications belong to this framework. From an application perspective, described use cases fall into the following categories:

- **XR (eXtended Reality)** refers to a range of applications that combine VR (Virtual Reality), AR (Augmented Reality) and MR (Mixed Reality) to create immersive digital experiences.
- **Robotics** refers to the use of a single or a group of collaborative robots to achieve smart connectivity or complete tasks that may be beyond human capability, with impacts on both industrial productivity and human wellbeing.
- **Environmental awareness** enables better understanding of the surrounding environment, which can improve operational safety and efficiency, and contribute to goals such as sustainability or climate action.
- **Local area collaboration** refers to collaboration among devices in proximity, which enhances the overall transmission efficiency. The collaboration can involve different types of devices.
- **Ultra-high data rate transmission** refers to continuous, real-time, and high-speed data transmission, including transport layer, access layer, or device to device communications.
- **Industrial control and management:** Smart industrial and industrial automation is a part of 6G frontiers, which requires accurate control and efficient management towards a more responsible consumption and production industry.
- **Wire/cable/fibre replacement:** The use of wire, cable or fibre can be costly and inefficient in many scenarios. In this regard, wireless communication is considered a promising alternative.
- **Health, wellbeing, education:** Technology can improve the quality of life and bring societal value in various fields.
- **Digital twin** refers to running a digital model of the physical world to realize the convergence of virtual and physical worlds.

The above use cases can be categorized based on their associated applications as given in table 9 and depicted in figure 36.

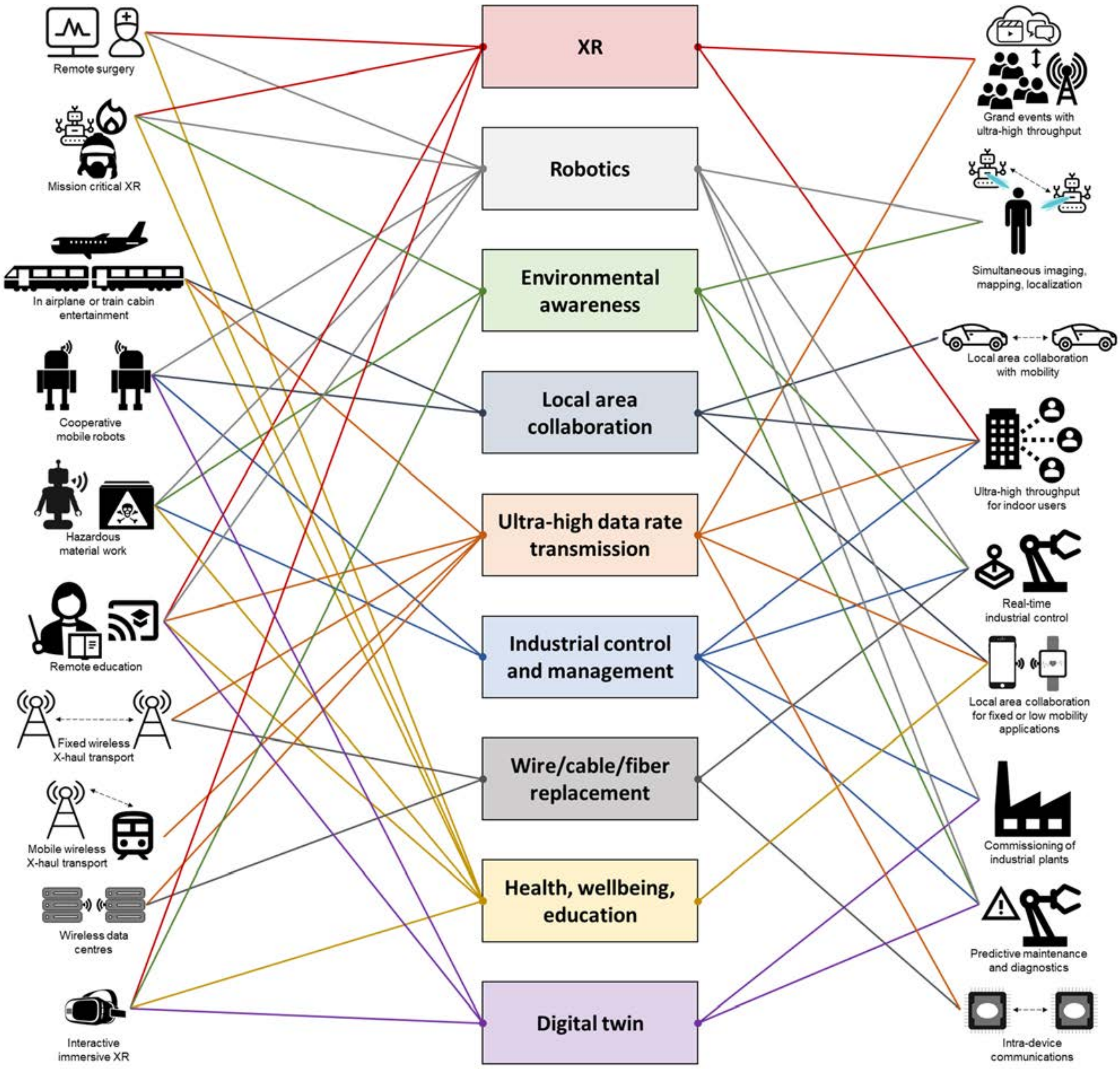

Figure 36: Use case mapping to application areas

Table 9: Use cases mapping to application areas

Application / Use case	XR	Robotics	Environmental awareness	Local area collaboration	Ultra-high data rate transmission	Industrial control and management	Wire/cable/fibre replacement	Health, wellbeing, education	Digital twin
Remote surgery	Y	Y						Y	
In-airplane or train cabin entertainment				Y	Y			Y	
Cooperative mobile robots		Y		Y		Y			Y
Hazardous material work		Y	Y			Y		Y	
Remote education	Y	Y			Y			Y	Y
Wireless X-haul transport for fixed link					Y		Y		
Wireless mobile X-haul transport					Y				
Wireless data centres					Y		Y		
Interactive immersive XR	Y		Y					Y	Y
Mission critical XR	Y	Y	Y					Y	
Real-time industrial control		Y	Y			Y	Y		
Simultaneous imaging, mapping, localization		Y	Y						
Commissioning of industrial plants		Y				Y			Y
Grand events with ultra-high throughput	Y				Y				
Ultra-high throughput for indoor users	Y			Y	Y	Y			
Intra-device communications					Y		Y		
Local area collaboration for fixed or low mobility applications				Y	Y			Y	
Local area collaboration for vehicular applications				Y					
Predictive maintenance and diagnostics		Y	Y			Y			Y

5.4 Enabling Technologies

5.4.0 Overview of enabling technologies

As described in the present document, communication systems operating in THz spectrum can be utilized to enable some emerging 6G use cases. To indeed realize the benefits, several additional key enabling technologies are required. From this angle, the enabling technologies identified and described in the use case sub-clauses are summarized in table 10.

Table 10: Enabling technologies for identified use cases

Use case \ Enabling Technology	AI/ML	Advanced MIMO	RIS	Advanced relays	Sensing, imaging, positioning	Energy efficient design for portable devices	D2D, mesh networks	Edge computing
Remote surgery	Y	Y			Y	Y		Y
In-airplane or train cabin entertainment		Y		Y	Y	Y	Y	Y
Cooperative mobile robots			Y		Y	Y	Y	Y
Hazardous material work					Y	Y		
Remote education	Y				Y	Y		Y
Wireless X-haul transport for fixed link		Y						
Wireless mobile X-haul transport		Y						
Wireless data centres		Y	Y					
Interactive immersive XR		Y	Y	Y	Y	Y	Y	Y
Mission critical XR					Y	Y	Y	Y
Real-time industrial control			Y		Y			Y
Simultaneous imaging, mapping, localization	Y				Y	Y		
Commissioning of industrial plants	Y				Y			Y
Grand events with ultra-high throughput		Y				Y		
Ultra-high throughput for indoor users		Y		Y		Y		
Intra-device communications						Y		
Local area collaboration for fixed or low mobility applications						Y	Y	
Local area collaboration for vehicular applications						Y	Y	
Predictive maintenance and diagnostics	Y							Y
NOTE: This mapping is not exhaustive, most enabling technologies are applicable to some extent to all use cases.								

5.4.1 AI/ML

Artificial Intelligence (AI), especially Machine Learning (ML), is considered as a promising tool for data analysis, and for exploiting data-driven model to handle the dynamic and especially non-linear environments or systems experienced in wireless communication and/or sensing. Table 10 shows the use cases that can largely benefit from AI/ML from data fusion and pattern recognition perspectives.

5.4.2 Advanced MIMO

MIMO has been a fundamental technology to enhance the overall system performance and user experience by improving data rate and reliability. The extremely short wavelength at THz allows for ultra-massive MIMO, which together with the wideband spectrum and severe propagation condition at THz necessitate the more advanced MIMO technologies. MIMO is particularly important for the use cases requiring ultra-high throughput, as shown in table 10.

5.4.3 Reflective Intelligent Surfaces (RIS)

RIS is a programmable surface structure able to control the reflection of electromagnetic waves by changing its electric and magnetic properties. As reported in table 10, RIS can efficiently improve communication link budget (especially when obstacles exist) and/or sensing accuracy needed by several use cases.

5.4.4 Advanced relays

In addition to the severe propagation conditions experienced at THz frequencies, the link quality is further degraded significantly due to the Outdoor-to-Indoor (O2I) penetration loss. In these scenarios, advanced relays are considered as a key enabler to efficiently utilize the THz bands and achieve ultra-high throughputs in indoor environments. For example, some types of advanced relays have the capability to receive data at one frequency (e.g. FR1), process and further transmit the data at another frequency (e.g. THz), as illustrated in figure 37. In this way, both the preferable propagation conditions at lower frequency bands and largely available spectrum at THz can be well utilized.

Furthermore, for use cases requiring high data rates in indoor environments as reported in table 9, high-rank MIMO transmission can in theory fulfil the demanding data rate requirements. However, in practice the number of deployed antennas at a UE (e.g. mobile phone, watch, glasses, etc.) is limited due to the form factor constraint, which poses hurdles towards realizing the potential high-rank MIMO gain. In this regard, advanced relays can be considered promising as they can be designed to have much more relaxed form factor constraint compared to a normal indoor UE in terms of e.g. a larger number of antennas.

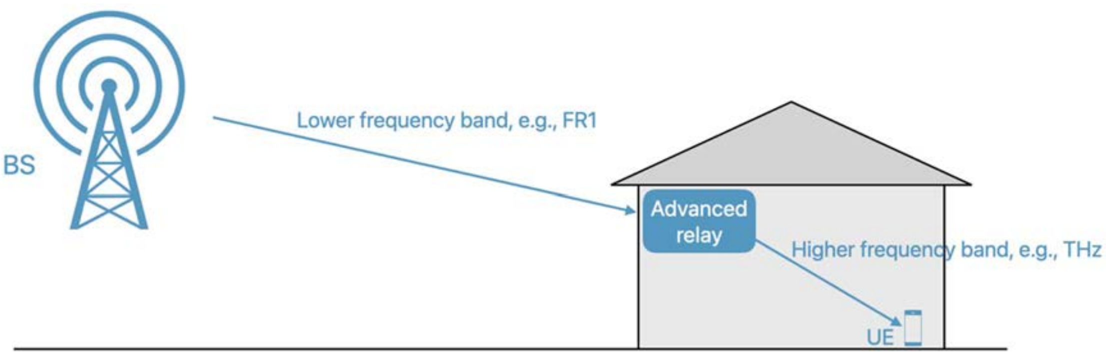

Figure 37: Advanced relay assisted transmission for indoor user

5.4.5 Sensing, imaging, positioning

Accurate positioning, sensing and imaging are crucial for many XR, robotics, and environmental awareness related use case, where the wide bandwidth available at THz is seen a beneficial characteristic. Furthermore, Integrated Sensing And Communication (ISAC) is deemed an efficient manner to make use of resources (time/frequency/spatial/power/hardware, etc.) for both communication and sensing.

5.4.6 Energy efficient design

Energy efficient design is a pre-requisite to all THz-based communications to close the link budget. This is even more stringent for portable devices where battery life is a concern. More generally, green technologies are critical for achieving sustainability of 6G, where power consumption and energy efficiency are considered key design aspects for all identified use cases. In particular, for the potentially large number of antennas deployed at THz, the power consumption reduction can be more challenging and be the key consideration for portable devices (see table 10).

5.4.7 Device-to-device communication and mesh network

Due to the rapidly increased density of wireless devices, the collaboration and/or coordination in proximity region becomes necessary and effective. As reported in table 10, some use cases largely rely on or benefit from device-to-device and mesh networking.

5.4.8 Edge computing

Edge computing is a distributed computing paradigm that moves the computer storage and processing to the edge of the network. Edge computing is considered an efficient manner to reduce end-to-end latency, which is the key for many applications and use cases with stringent delay requirements, as reported in table 10.

6 Conclusions and recommendations

The present document identified 19 use cases either enabled by or highly benefiting from the use of THz communications:

- Remote surgery
- In-airplane or train cabin entertainment
- Cooperative mobile robots
- Hazardous material work
- Remote education
- Fixed point to point wireless applications
- Mobile wireless X-haul transport
- Wireless data centres
- Interactive immersive XR
- Mission critical XR
- Real-time industrial control
- Simultaneous imaging, mapping and localization
- Commissioning of industrial plants
- Grand events with ultra-high throughput
- Ultra-high throughput for indoor users
- Intra-device communications
- Local area collaboration for fixed or low mobility applications
- Local area collaboration for vehicular applications
- Predictive maintenance and diagnostics

For each identified use case, the present document provides description of the deployment scenario, pre-conditions required for the use case deployment, an example of service flows through a communication system supporting the use case, post-conditions enabled by the use case, identified potential requirements, and description of the physical environment, including propagation aspects, range, and mobility. In some cases, the present document further identifies enabling technologies either unlocking or being highly beneficial for the associated use cases.

The present document provides a mapping of the identified use cases and deployment scenarios to relevant channel measurements scenarios currently available in the literature. The physical environments corresponding to identified use cases are falling into one or several of the following categories:

- Indoor
    - On-body
    - Medical facilities
    - Living room
    - Airplane cabin
    - Train cabin
    - Factory
    - Classroom
    - Data centre
    - Hallway
    - Meeting room
    - Office
    - Intra-machine/device
- Outdoor
    - Open space
    - Highway
    - Urban street
    - Urban canyon
    - Stadium
    - Square

Several channel measurements for most of the physical environments identified by the ISG THz are reported in the literature. However, for some environments and certain scenarios, measurements are still lacking, such as for:

- Indoor: on-body, medical and living room
- Outdoor: stadium and square
- Mobile environments

Furthermore, while channel models for THz bands are available, they do not cover all of the use cases and physical environments identified in the present document. It is therefore recommended to perform channel measurements and develop channel models in the THz bands for the identified use cases with typical deployment scenarios for both indoor and outdoor environments within the scope of ETSI GR THz 003 [i.67].

It is recommended to take into account the use cases and physical environments identified in the present document during RF hardware modeling within the scope of ETSI GR THz 004 [i.142]. For example, suitable link budget analysis is recommended to be performed for the various use cases to determine power levels of signal, noise and impairments within the RF transceivers. Also, depending on the physical separation between transmitter and receiver in the case of communications or between transmitter and target in the case of sensing, near field effects of the electromagnetic waves on the RF hardware model and on the size of the antenna arrays are recommended to be considered.

The present document further discusses considerations on use case characterization. From mobility perspective, use cases cover fixed links, limited (known) mobility links, and medium/high mobility links. The type of mobility impacts both:

- the physical environment characteristics and thus the channel models to be developed to support the identified use cases; and
- the technologies that need to be implemented in order to support the identified use cases (e.g. MIMO, beam alignment, beam tracking, etc.).

It can be noted that, from a technology perspective, many of the identified use cases are related to ISAC. In this context the role of imaging, sensing and localization is two-fold. On one hand the THz spectrum has specific features, that makes imaging, sensing and localization particularly suitable in supporting several applications of the identified use cases. On the other hand, imaging, sensing and localization in THz bands are also enabling technologies to improve communications.

Identified use cases respond to both technological advancements and societal value needs, in the framework of the United Nantions sustainable development goals. From an area of application perspective, described use cases fall into the following categories:

- EXtended Reality (XR) including Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR)
- Robotics
- Environmental awareness
- Local area collaboration
- Ultra-high data rate transmission
- Industrial control and management
- Wire/cable/fibre replacement
- Health, wellbeing, education
- Digital twin

In the following, a list of consolidated requirements and potential KPIs related to the identified use cases is provided:

- The required latency ranges between 25 µs and 300 ms. Some use cases require extremely low latencies below 0,5 ms, such as fixed wireless X-haul transport, cooperative mobile robots, real time industrial control, and commissioning of industrial plants.
- The data rate requirements ranges from 10 Mbps and potentially up to a few Tbps. Use cases on remote education, grand events with ultra-high throughput, and ultra-high throughput for indoor users require or may benefit from extremely high data rates above 1 Tbps.
- The required reliability is between 99,9 % and 99,9999999 %. Use case dealing with motion control and industrial applications, such as cooperative mobile robots, real-time industrial control, and commissioning of industrial plants, require extremely reliable operations.
- The required connection density can be up to 2 million devices/km^2. The use cases on grand events with ultra-high throughput, ultra-high throughput for indoor users, and local area collaboration with mobility require the ability to support an exceptionally-high user density.
- Some use cases have requirements related to sensing KPIs, such interactive immersive XR and simultaneous imaging, mapping, and localization, which require a localization accuracy down to 0,5 cm.

The present document identifies the following key enabling technologies as being beneficial for the identified use cases:

- AI/ML
- Advanced MIMO
- Reflective intelligent surfaces
- Advanced relays
- Positioning, sensing and ISAC
- Energy efficient design
- Device to device communications and mesh networks
- Edge computing

History

Document history		
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