O-RAN Next Generation Research Group (nGRG)

Contributed Research Report

Use Case Analysis on mmWave Antenna Distribution (mWAD)

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Executive summary

In the dynamic landscape of wireless communication, the arrival of 6G technology emerges as a transformative force, opening the way for exciting capabilities. This research report delves into the complex domain of mmWave Antenna Distribution (mWAD), a critical aspect in the evolution from 5G to 6G. The underlying concept is to interpret the potential of mmWave technology, particularly focusing on its applications in various areas and challenges.

The introduction establishes the groundwork by highlighting the distinctive features of sub6 and mmWave in 5G networks and prepares for the upcoming needs of 6G. As we envision a future where 6G enables seamless connectivity for over 500 billion devices [1], this report underscores the essential role of mmWave technology. However, the inherent limitations of mmWave, such as shorter “reach” and less “penetration”, present challenges in the pursuit of cost-effective 6G applications.

Diving into the technical details, the report categorizes radio frequency wave carrying techniques into bare radio and tunneled radio. These categories, including technologies like massive Multiple Input Multiple Output (mMIMO) and distributed antenna systems, are analyzed to comprehend their unique attributes and synergies. The significance of antenna distribution in mitigating challenges and optimizing mmWave networks is brought to the forefront.

As we shift focus to the objectives and goals of the study, the primary aim is to survey 6G use cases, specifically identifying applications that necessitate mmWave access through distributed antennas. The subsequent analysis seeks to bridge the gap between application requirements and existing specifications, offering insights crucial for steering the trajectory of 6G development.

In this survey, we analyzed 170 6G use cases from 4 global documents, categorized them into 29 integrated use cases, and extracted 31 requirements. A deeper requirement analysis was conducted for use cases where the application of mWAD is anticipated, and a gap analysis was performed in comparison with 5G technologies.

In 6G networks it is expected the convergence of the physical and cyber worlds will accelerate, enabling the sharing of various experiences without the constraints of location. To realize this, an even greater data rate and lower latency communication will be required. For instance, the data rates needed for replicating real objects in virtual spaces for live sports, live music, or the metaverse demand 14-230 Gbps per object for uplink, while on the viewing side, 48-200 Gbps for downlink is necessary. These requirements exceed the capabilities of 5G.

This report demonstrates how mWAD can contribute to realizing such a future and clearly identifies its challenges. Furthermore, it discusses the challenges associated with mWAD, introducing potential technologies and initiatives that could serve as solutions.

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List of abbreviations

AGV	Autmatic Guided Vehicle
AI	Artificial Intelligence
AIC	AI Integrated Communications
A-RoF	Analog Radio over Fiber
B5G	Beyond 5G
CPS	Cyber-Physical Systems
CAT6	Category 6
DAS	Distributed Antenna System
D-MIMO	Distributed MIMO
DT	Digital Twins
DWDM	Dense Wavelength Division Multiplexing
E2E	End to End
eCPRI	enhanced Common Public Radio Interface
eMBB	Enhanced Mobile Broadband
FWA	Fixed Wireless Access
IAB	Integrated Access and Backhaul
IOWN-GF	Innovative Optical and Wireless Network Global Forum
IMDD	Intensity Modulation and Direct Detection
LOS	Line of Sight
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
mMTC	massive Machine Type Communications
mWAD	mmWave Antenna Distribution
mmWave	Millimeter wave
MNO	Mobile Network Operator
nGRG	Next Generation Research Group
NLOS	Non Line of Sight
NTN	Non-Terrestrial Network
O-CU	O-RAN Central Unit
O-DU	O-RAN Distributed Unit
O-RU	O-RAN Radio Unit
PON	Passive Optical Network
PtP	Point to Point
RAN	Radio Access Network
RIS	Reconfigurable Intelligent Surface
RF	Radio Frequency
RS	Research Stream
SCM	Subcarrier Multiplexing
SDGs	Sustainable Development Goals
Sub6	Sub 6GHz
SUC	Summrized Use Case
UE	User Equipment
URLCC	Ultra Reliable Low Latency Communications
WAN	Wireless Access Network
WDM	Wavelength Division Multiplexing

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1 Introduction

1.1 Background

In the 5G era, two radio frequency ranges were added: sub6 and millimeter wave (mmWave). mmWave spectrum has a significant disparity from sub6 and can support channel bandwidths exceeding 400MHz or even 1GHz, offering 5G usage scenarios such as enhanced Mobile Broadband (eMBB). This allows for deployment across a wide range of scenarios, from small cell to enterprise to micro to macro, accommodating various deployment strategies as technology evolves.

As we advance towards 6G and beyond 6G, there are ongoing discussions on the required capabilities. For instance, eMBB is expected to demand 100Gbps [12] and more, thus, requiring even higher frequencies from 100GHz up to 300GHz for allocation and deployment. However, it is well-known that although mmWave suffers from higher propagation loss, higher range of carrier frequencies of mmWave from 100GHz up to 300GHz suffer are even more constrained by range limitation. The objective for 6G is to establish connectivity for more than 500 billion devices, including vehicles, appliances, and urban structures, within a high-speed communication network. Developing mmWave solutions at a reasonable cost will be a key factor in enabling 6G applications. Furthermore, higher frequency radio signals have limited reach, resulting in a substantial increase in the number of antennas required to achieve the desired performance compared to lower frequency ranges. Consequently, the ability to efficiently utilize mmWave technology at a reasonable cost will be a crucial determinant in shaping the development and implementation of 6G applications.

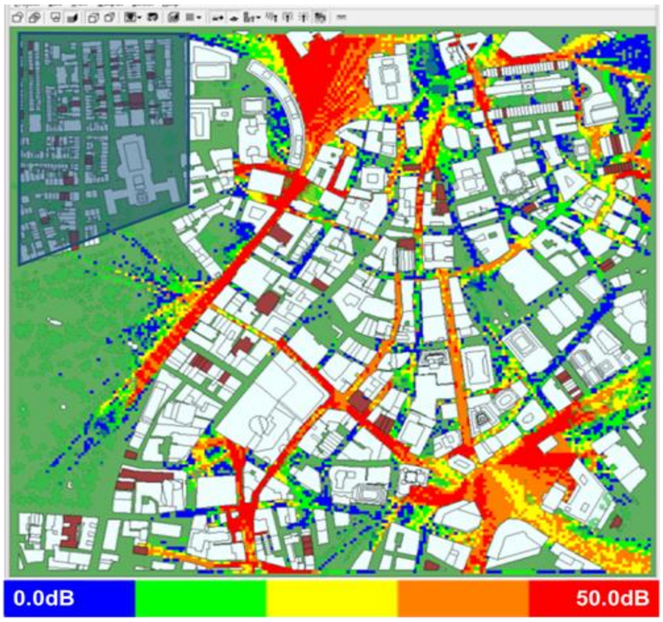


Figure 1 Downlink coverage SINR 28GHz [2] (revised for legibility)

An illustration of mmWave communication propagation in both line-of-sight (LOS) and non-line-of-sight (NLOS) environments is depicted in Figure 1. The illustration showcases the signal following street corridors and low wall penetration of mmWave signals [2]. Consequently, the use of mmWave technology solely based on air radio relaying is not feasible, particularly in scenarios with numerous obstacles.

In this research report, we divide radio wave propagation techniques into two categories from attenuation point of view: *bare radio* and *tunneled radio* techniques as shown in Figure 2. Tunneled radio techniques include antenna distribution, while various technologies such as repeaters, reflectors, integrated access and backhaul (IAB) fall under bare radio techniques. In the mmWave spectrum, mMIMO technology, which uses a massive number of antenna elements, is a key factor in achieving effective use of higher frequency bands [3]. Distributed MIMO (D-MIMO) combined with beam management aspects of 5G New Radio (5G NR) air interface is a promising method for radio access network (RAN) systems, especially in high-frequency bands. When D-MIMO is combined with the NR air interface, it allows for the utilization of high-frequency bands (which can support large bandwidths and high data rates) more efficiently. The distributed nature of D-MIMO ensures a more uniform service quality even in high-frequency bands, which traditionally have issues with signal propagation [4], [5], [6].

Tunneled radio techniques used in distributed antenna systems (DAS) have been widely utilized for in-building mobile network deployment in the 4G era. These technologies are useful for carrying radio signals to any location required, regardless of obstacles or radio conditions in the path. In this document we use terminology *distributed* as in location at different cell-coverage sites (opposite to distribution as in a clustered set of antennas (e.g., array) at a single cell. Bare radio techniques rely on radio waves in the air, which can be affected by various obstacles on the path, such as walls, doors, human bodies, and weather conditions. In contrast, tunneled radio techniques use cables like co-axial, Category 6 (CAT6), and optical fiber to carry radio signals, and the only disturbance is attenuation of the cable medium. Depending on the tunneling technique, the reachable distance can vary, and in some cases, it can be tens of kilometers. This is the primary advantage of tunneled radio when compared to bare radio. Nevertheless, tunneled radio requires more cable installations, which is a drawback.

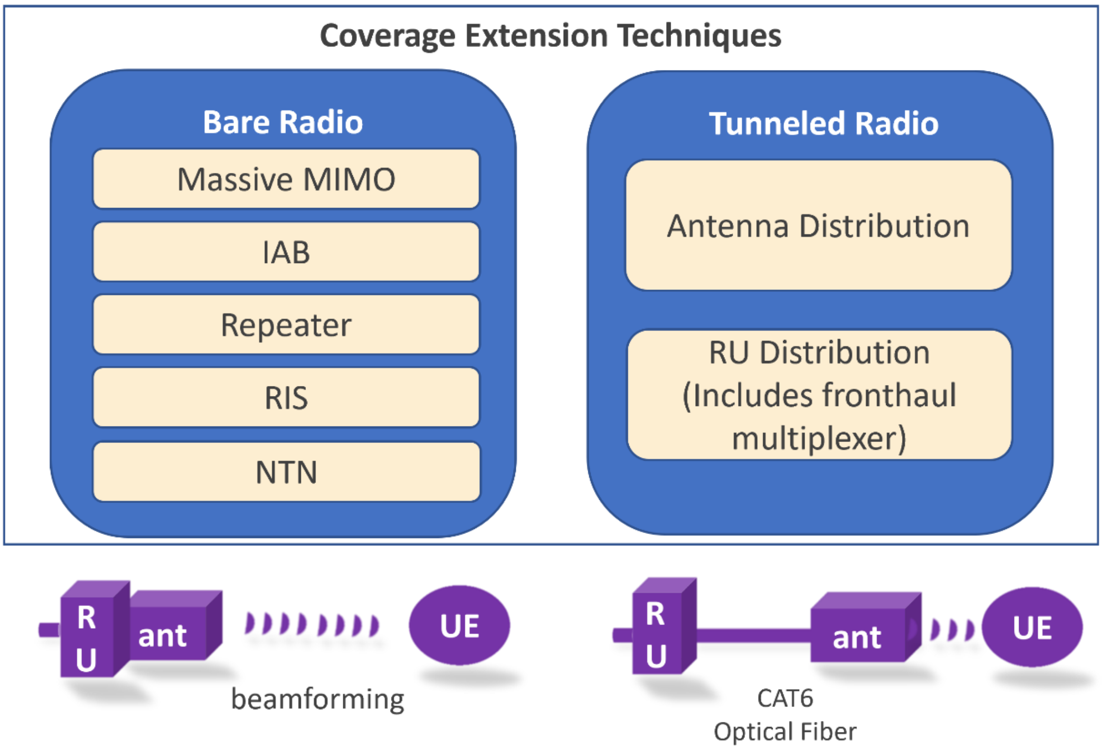


Figure 2 Two categories of coverage extension techniques

Bare radio and tunneled radio techniques possess different characteristics but can be used in conjunction and complement each other. For instance, a repeater can transmit the received radio signal through CAT6 cable. During the 6G era, a combination of techniques will be necessary to master higher frequency radio. Regarding D-MIMO deployment, the distribution of a massive number of antennas is inevitable. Nevertheless, as of today there is limited discussions about tunneling techniques for mmWave, whereas numerous discussions focus on mMIMO.

In this research report, we delve into the transformative potential of 6G technology and its exciting capabilities, particularly focusing on the evolution from 5G to 6G. Building upon the tunnelled radio topology, we investigate the concept of mWAD, a crucial technique aimed at efficiently distributing a large number of mmWave antennas for optimal coverage and data rate enhancement in B5G/6G networks. This report explores the potentials and applications of mmWave technology across various domains, while addressing the associated challenges.

As of today, many organizations have published 6G use cases, including NGMN [7], Hexa-X [8], Next G Alliance [9] and more. To represent the reason why we should prioritize tunneled radio, two use cases are outlined below, however there many additional use cases that can be incorporated into this research area:

1.2 6G fixed wireless access (FWA)

While 5G mmWave FWA networks have the potential to deliver high-speed, low-latency connectivity, several challenges still require attention. These challenges include coverage, bandwidth, interference, cost, LOS loss requirements, and indoor coverage. Although FWA networks in 5G have relatively low latency compared to traditional broadband, there is still room for improvement. In 6G, there is a need to develop technologies that can further reduce latency and enhance network configuration response, particularly for real-time applications like gaming and virtual reality (VR). Addressing these challenges will be vital for the success of mmWave FWA in B5G and 6G. We haven’t seen much momentum around mmWave in the 5G market although it has come up recently in the context of FWA. Carriers seeking revenue growth by offering fixed broadband services could consider utilizing mmWave technology, assuming it can be deployed economically.

To address the challenges in 6G, antenna distribution emerges as a potential solution for FWA networks operating in mmWave bands. Antenna distribution, here, involves deploying multiple antennas in specific areas, with each antenna serving a different user. This approach can mitigate limited coverage and interference issues by enabling signal direction (beam narrowing during beamforming from multiple antenna- i.e., arrays) toward specific areas, thereby enhancing overall network performance. Moreover, advanced beamforming techniques can be used to improve the LOS challenges, *enabling beam-sweeping to find the best path around obstacles*. Advanced usage of those techniques can further help optimize the cost efficiency of mmWave networks by enabling more efficient use of the available spectrum. Antenna distribution can significantly enhance energy efficiency in 6G FWA networks, by enabling beamforming, hybrid beamforming, mMIMO, intelligent antenna systems, and energy harvesting. These techniques can decrease the energy required for signal transmission, enabling FWA networks to operate with greater efficiency and sustainability.

In summary, antenna distribution is expected to play a critical role in the evolution of mmWave networks within the 6G context.

1.3 Robot/Cobot

Looking at robotics ([7], [8]) use cases, robots and cobots are expected to be used in various building environments, ranging from residences to factories. Human-machine and machine-machine interactions will be required for residential cobots to make decisions. For instance, a vacuum cleaner equipped with a video camera could stream data to a local server for real-time processing and trajectory planning, with sensors designed to prevent collisions and offer assistance. Reliability is essential as cobots interact with both humans and machines.

Robots in factories may use automated communication to identify one another, exchange “intentions”, and negotiate actions for conducting collaborative production tasks among mobile machineries. Real-time communication, low latency, time synchronization, and precise positioning are necessary for Automated Guided Vehicles (AGVs) to transfer goods to lifts. Considering the potentially large size of industrial applications like factories and construction zones, a substantial number of antennas may be necessary. Reliability is also essential as robots will interact with both humans and machines. These robots and cobots require real-time, low-latency, and broadband uplink communication, as along with precise positioning and time synchronization. Dependability, cost-efficiency, and sustainability are the fundamental requirements.

Reliability is crucial for robots in industrial contexts, demanding extreme performance in terms of latency and positioning. By offering higher bandwidth, enabling fast data transmission, and accurate position sensing, mmWave technology is very promising in delivering these capabilities, but expecting a LOS environment within a building is unrealistic. Tunneling coverage enhancement technologies are required, along with bare radio techniques such as mMIMO. Figure 1 illustrates mmWave propagation characteristics in both LOS and NLOS environments, highlighting the straightness and reliability of mmWave signals. To ensure communications for reliability, numerous antennas could be distributed across larger factory or construction zones. These antennas should be lightweight and equipped with intelligent energy-saving features that do not compromise dependability.

1.4 Objectives and Goals

The primary goal of this research report is to survey current Beyond 5G (B5G) and 6G use cases to identify applications that require mmWave access through distributed antennas. The identified applications will be analyzed to assess the gap between their requirements and existing specifications.

2 Research methodology

This chapter will briefly describe the methodology used to conduct this research work.

2.1 Overall process flow

Many organizations have already published documents related to 6G, and numerous 6G use cases have been introduced in these publications. Therefore, this document does not generate new 6G use cases. Instead, we will organize the requirements for existing 6G use cases by analyzing them and assessing any gaps. Detailed steps are as follows:

- *Step 1*: Selecting documents that introduce 6G use cases.
- *Step 2*: Understanding the characteristics of mWAD: In this step, to understand the characteristics of mWAD, we generate a Pros and Cons table regarding existing coverage extension technologies.
- *Step 3*: Analyzing use case requirements: in this step we investigate the requirements for each 6G use case to select 6G use cases (Step 4) where antenna extension could potentially be applied based on the requirements revealed in Step 3 and characteristics unveiled in Step 2.
- *Step 4*: Selecting appropriate use cases.
- *Step 5*: Investigating detailed requirements of the selected use cases: in this step we delve deeper into the requirements of the selected use cases.
- *Step 6*: Analyzing any gaps between the requirements and existing technologies: In this step we analyze the gaps between requirements explored in Step 5 and existing technologies.

Each step is described in more details in chapter 3.

3 Use case analysis

Global discussions on the standardization of 6G for the 2030s have already began, influenced by the competitive landscape in the development of 5G. Initiatives examining 5G internationally started to take form around 2012, approximately 8 years before the launch of 5G. In contrast, discussions pertaining to 6G commenced around 2018, preceding the anticipated launch by 12 years. Notable initiatives in this early phase include the 6Genesis Project led by Oulu University in Finland and efforts in the United States to intensify development. Additionally, the Federal Communications Commission (FCC) decision in the US to allocate terahertz waves for research purposes contributed to these early global endeavors, as outlined in Figure 3. Through the global 6G initiatives, various organizations have introduced significant number of 6G use cases [10].

In this chapter we discuss B5G and 6G use cases, and their requirements. We will then continue reviewing their required specs and find out any gaps between current generation (5G) and what are required for the use cases in B5G/6G. Finally, we close the chapter by picking up the most suitable use cases that can be leveraged using mWAD coverage techniques. The output of this chapter is very useful and may be an outstanding foundation for further research in the community and other standard development organizations working on the next generation cellular communication.

3.1 Selecting 6G documents

To investigate the use cases, the following documents have been selected:

1. **NGNM** "NGMN Use Cases and Analysis" [7]: NGNM has a long history of contributing to mobile networks and maintains a strong relationship with 3GPP.
2. **Hexa-X** Deliverable D1.2**,** "Expanded 6G vision, use cases and societal values" [8]: To align with European perspectives, Hexa-X has been chosen.
3. **Next G Alliance Report**, "6G Applications and Use Cases" [9]. To align with North American perspectives, NextG Alliance, a U.S. based organization, has been chosen.
4. **B5GPC White paper "**Beyond 5G White paper –Message to the 2030s" [11]: To align with Asian perspectives, beyond 5G Promotion Council (B5GPC) has been selected. B5GPC boasts a significant number of applications, surpassing 100.

3.2 Understanding the characteristics of mWAD

To understand the features of mWAD technique, O-RAN ALLIANCE nGRG RS01 has developed and reviewed a concise table outlining the pros and cons of various coverage techniques. Table 1 and Table 2 list the common features of the techniques introduced in section 1.1. It is important to note that the only purpose of this table is to understand the characteristics of mWAD, as opposed to establishing a hierarchy of technique superiority or inferiority. Furthermore, the highlighted techniques are not mutually exclusive; they can be employed in a variety of combinations.

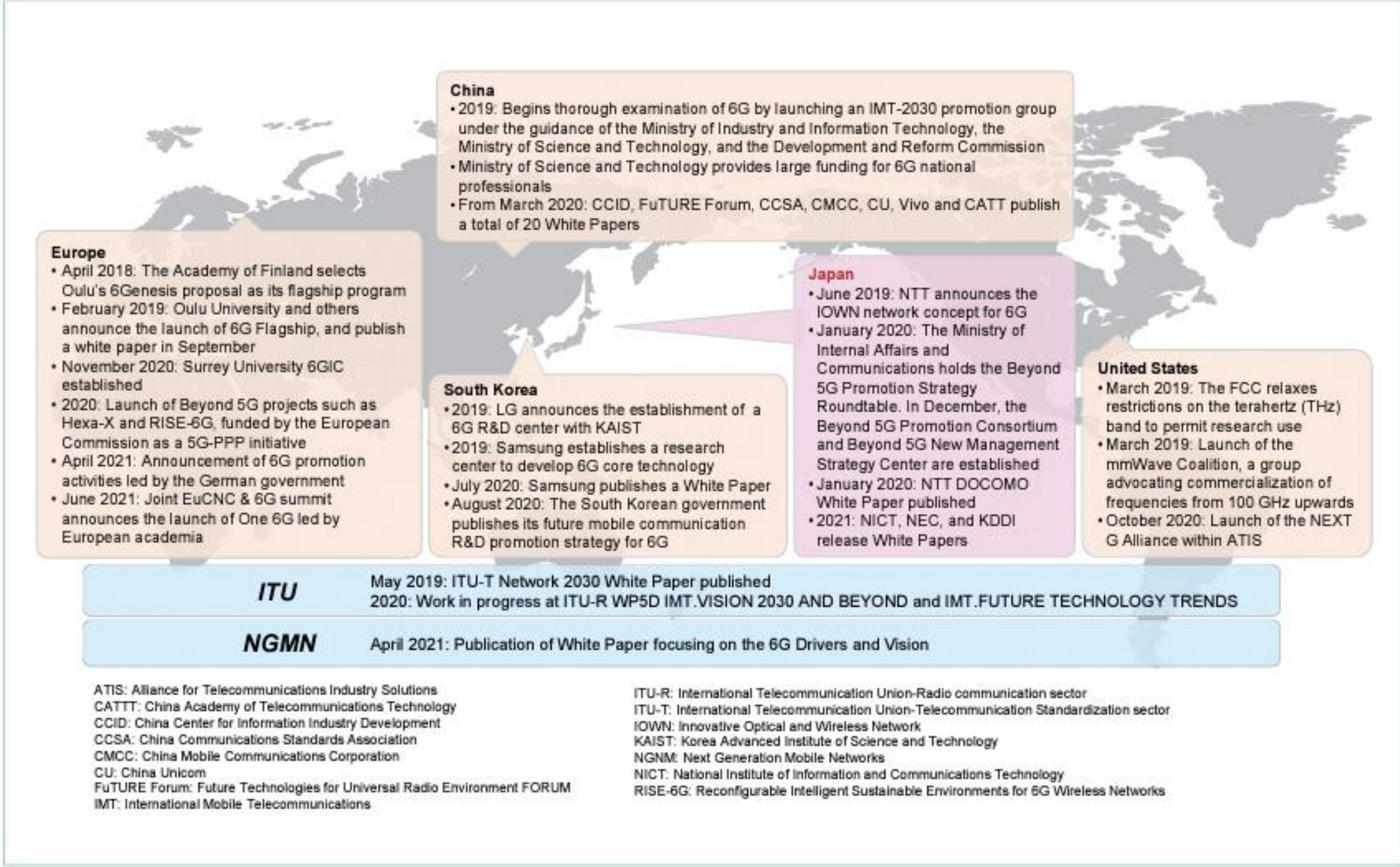
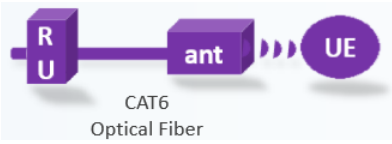
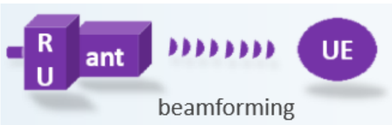


Figure 3 Global Trends for B5G & 6G [10]

Table 1 Pros and Cons of Tunneled and Bare radio techniques

Radio Type	Pros	Cons
Tunneled Radio  	- Wave path condition agnostic (Obstacles, Rain/Humidity, Water, moving objects, Interference) - The antenna can be placed further to provide connectivity in far remote areas. - Offers flexibility in designing coverage patterns and optimizing network performance and energy efficiency.	- Needs wires and installation cost. - Requires careful planning and coordination for optimal antenna placement. - Limitation of IQ sample data - High cost of fronthaul traffic
Bare Radio  	- No cost for wires (propagation medium) - Quick installation	- Affected by wave path condition (Obstacles, Rain/Humidity, water, moving objects, interference) - Relatively short reachable distance

Looking at more specific coverage extensions techniques being used in telecommunication; we can focus on methods described in Figure 2. Later in chapter 4, when we are investigating various use cases and their required features, we will then have a reasonable reasoning on if mWAD can be a suitable solution to leverage those use cases, based on its unique characteristics. Table 2 summarizes the pros and cons for each method. This table provides a good insight on the reason that mWAD can be considered as a strong candidate for mmWave deployment scenarios in 5G, B5G and 6G ecosystems.

Table 2 Pros and Cons of commonly used coverage extension techniques

Technique	Pros	Cons
mWAD (Tunneled Radio)	- Pros of Tunneled Radio (Table 1) - Simple distributed radio unit (low cost) - Lightweight antenna module (easy installation)	- Cons of Tunneled Radio (Table 1) - Fronthaul is shared by multiple antennas

	- Provides spatial diversity, enhancing signal reliability and mitigating fading effects. - Helps manage interference by optimizing radiation patterns. - No handover - Same radio from multiple antennas, improving RF quality. - Low energy consumption	
Beamforming (Bare Radio)	- Pros of Bare Radio (Table 1) - Possible to extend propagation distance. - Space multiplexing (MU-MIMO)	- Cons of Bare Radio (Table 1) - Short reachable distance (e.g., < 300m) - Requires accurate channel information for beam steering, which may introduce latency and traffic. - Complex beamforming algorithms and hardware increase system complexity, cost and energy consumption.
Repeater (Bare Radio)	- Pros of Bare Radio (Table 1) - Possible to extend propagation distance - Relatively low cost - Easy installation - Across the wall - Multi hops.	- Cons of Bare Radio (Table 1) - Each hop has limited distance (e.g., < 300m) - Accumulated latency
Reflector (Bare Radio)	- Pros of Bare Radio (Table 1) - Possible to extend propagation distance. - Easy installation - Multi hops. - Helps redirect the signal around obstacles or toward specific areas. - No energy consumption (passive element)	- Cons of Bare Radio (Table 1) - Limited distance (e.g., <300m in total) - Accumulated latency - Limited effectiveness in mitigating multi-path fading compared to other techniques. - Requires careful positioning and alignment for optimal performance.
RIS (Bare Radio)	- Pros of Bare Radio (Table 1) - Multi hops.	- Cons of Bare Radio (Table 1) - Each hop has limited distance (e.g., <300m)

	- Enables beamforming, signal shaping, and interference mitigation. - Enhances coverage, capacity, and energy efficiency.	- Accumulated latency - Adds complexity and cost to the system design and deployment.
IAB (Bare Radio)	- Pros of Bare Radio (Table 1) - Possible to extend propagation distance. - Multi hops. - Mobile IAB for emergency/ad-hoc requirement - Combines access and backhaul functionalities in a single mmWave system. - Improves network scalability and flexibility.	- Cons of Bare Radio (Table 1) - Each hop has limited distance (e.g., <300) - Accumulated latency - Accumulated traffic - Requires synchronization and coordination between access and backhaul nodes. - Higher energy consumption (due to backhaul and access service)
NTN (Bare Radio)	- Pros of Bare Radio (Table 1) - Extends coverage to remote or underserved areas. - Large coverage (e.g., cell with a radius of 50km ~ 100km) - Flexible	- Cons of Bare Radio (Table 1) - Higher latency compared to terrestrial networks.

As can be seen in Table 2, mWAD offers its substantial advantages in scenarios characterized by numerous obstacles, including solid walls, regions with high humidity, the presence of liquids, and various other unpredictable environment factors. Notably, mWAD not only provides a solution to these hurdles but also delivers exceptional stability, making it an invaluable asset in the development of highly reliable and predictable wireless networks. For instance, in urban environments with dense infrastructure and ever-changing atmospheric conditions, mWAD's performance remains consistent, ensuring uninterrupted connectivity and robust network design.

3.3 Exploring use cases and key capabilities for 6G

In the era of 6G, our daily lives will be transformed by ultra-high speed and ultra-reliable wireless connections, native Artificial Intelligence (AI), and advanced sensing technologies. Some capabilities such as eMBB, Ultra Reliable Low Latency Communications (URLLC), massive Machine Type Communications (mMTC), and others, are considered crucial for 6G. These capabilities aim to provide faster data speeds, support instantaneous response applications, allow large-scale device connectivity, and much more. As we develop towards 6G, we are expanding and redefining these capabilities to meet the demands of the future [12].

The documents introduced in section 3.1 cover various types of use cases and applications. Each of them has its own set of required functions and performances. This research report represents a comprehensive investigation into 170 diverse 6G use cases, seeking to clarify and categorize the sophisticated requirements essential for optimal performance.

3.3.1 Collecting 6G required capabilities

Utilizing a systematic approach, the study identified 31 key capabilities critical for the diverse array of these use cases, leveraging insights from an extensive review of the selected white papers. The 31 identified capabilities encapsulate a broad spectrum of requirements, addressing key aspects such as data rates, latency, coverage, and others. All the capabilities are listed in Table 3. Each capability represents a crucial facet contributing to the diverse demands posed by the plethora of 6G use cases. Table 3 shows abbreviations and correspondent features on 5G [13] and 6G [12] key capabilities and usage scenario.

Table 3 Key capabilities required in 6G use cases

Found capability	Symbol	5G key capabilities [13]	6G key capabilities [12]
eMBB	EMBB	Peak data rate	Peak data rate
URLLC	URLLC	Latency	Latency
mMTC	MMTC	Connection density	Connection density
User experience data rate	UDRAT	User experience data rate	User experience data rate
Spectrum efficiency	SPCEF	Spectrum efficiency	Spectrum efficiency
Mobility	MOB	Mobility	Mobility
Energy efficiency	ENEEF	Energy efficiency	Sustainability
Area traffic capacity	ACAP	Area traffic capacity	Area traffic capacity
Reliability	REL	–	Reliability
Security	SEC	–	Security, privacy, and resilience
Coverage	COV	–	Coverage
AI/ML	AI	–	Applicable AI related capabilities
Positioning	POS	–	Positioning
Time synchronization	TSYN	–	–
Network management	NETMN	–	–
Sensing	SENS	–	Sensing related capabilities
Computing	COMP	–	–
Cost efficiency	COST	–	–
IoT	IOT	–	–
Digital twin	DTWIN	–	–
Wearable device	WEARD	–	–
Functional safety	FSAFE	–	–
Local communications	LOCC	–	–
Anomaly detection	ANOMD	–	–
OTA update	UPDAT	–	–
Energy harvest	EHARV	–	–
Easy User Interface	EUI	–	–
Holographic/Immersive communications	HOLO	–	–
AR/VR/MR	XR	–	–
Remote operation	REMOP	–	–
Autonomous operation	AUTOP	–	–

*NOTE: “Interoperability” of 6G capabilities is not mapped.

3.3.2 Selecting appropriate use cases

Based on the requirements and characteristics of mWAD introduced in section 3.2, mWAD is beneficial for in-building use (since indoor environments entail shorter distances to UE) as well as in various weather conditions and crowded areas. There are various conditions and viewpoint to filter the mWAD-friendly use case. The term mWAD-friendly is implying that using mWAD technique, that specific use case can be leveraged to meet the required capabilities. Therefore, to simplify the selection process for 6G use cases, and led by knowledge of section 3.2, we have introduced some characteristics, listed in Table 4, such as Overlay Radio Frequency (RF), Low latency, Broadband etc. Capabilities of each use case are checked against these characteristics and if they are in good agreement, the use case will be considered mWAD-friendly.

Table 4 mWAD charactristics

Technology	Characteristcs
mmWave	Allowing overlay RF on sub6G network Helps overflowed sub6G network
	Broadband connectivity
	Low latency communication
Antenna distribution	Using same radio from multiple antennas
	Allowing no handover
	High quality radio
	Small size radio unit
	Low energy consumption - Only one AD/DA converter needed for multiple antennas)
	Can carry RF over long distance
	Suitable for any weather condition (rain/humidity/…)
	Suitable for use cases that needs mmWave for indoor building. - Beyond the walls and low-E glass)

Based on the findings from sections 3.2 and 3.3.1 and, we selected the mWAD-friendly use cases. For example, the key nature of mWAD-friendly use cases include:

1. The use case potentially occurs in in-door environment.
2. The use case potentially happens under various weather conditions, allowing for reliable performance under varying climate scenarios.
3. The use case involves carrying the radio through liquid environments (e.g., aquarium surrounded by tanks).
4. The use case requires carrying the radio through many obstacles' environments (e.g., factory with many obstacles, robots, machineries, automatic guided vehicles [AGVs]…).
5. The use case requires stable communications, ensuring consistent and uninterrupted data transmission (due to shorter distance between UE and antennas, mWAD minimizes interruptions and enhances radio quality).

We adopted broad selection criteria to ensure the inclusion of all important use cases. therefore, if a use case meets any of these conditions, it is considered for selection. The rules for filtering out mWAD-friendly use cases from our gathered 170 use cases are defined as below:

- **Condition 1:** mmWave is TRUE when one or more of its corresponding characteristics in Table 4 are met;
- **Condition 2:** Antenna distribution is TRUE when one or more of its corresponding characteristics in Table 4 are met
- **Condition 3:** Use case is mWAD-friendly if a use case satisfies **both conditions 1 and 2.**

It is worth noting that several use cases with overlapping applications and/or usage scene can be interpreted collectively, thereby providing a more comprehensive perspective. To enhance the study's cohesion, we have summarized the use cases in Table 5. For ease of reference, we will use the abbreviation 'SUC' to represent 'Summarized Use Case' throughout this paper. A comprehensive overview of various use cases is presented, highlighting key criteria and interpretations.

Table 5 Summarized use cases (SUC)

	SUC
1	3D Map Creation/Maintenance
2	Agriculture/Fishing/Mining
3	Art/Design/Creative work
4	Autonomous/Assisted Drive
5	Cashless Payments
6	Construction
7	Consumer Robot
8	Digital Divide Elimination
9	Education
10	Emergency/Disaster
11	Entertainment/Sports
12	Facility/Equipment Maintenance
13	Factory/Plant
14	Gaming
15	Government
16	Healthcare/Medical
17	Industrial Collaborative Robot
18	Insurance Service
19	Personalized User Experience
20	Program Update
21	Real Estate Management
22	Restaurant
23	Smart City
24	Social Security/Surveillance
25	Space Life
26	Supply Chain/Product Life Cycle Management
27	Sustainable Life
28	Travel Navigation
29	Warehouse/Logistics

3.3.3 Defining criteria for gap analysis

To assess the disparity between the requirements of the SUC and current 5G technology, it is essential to establish criteria based on fundamental indicators. The criteria outlined below will serve this purpose, with reference values drawn from "Recommendation ITU-R M.2083-0" informing their definition [13].

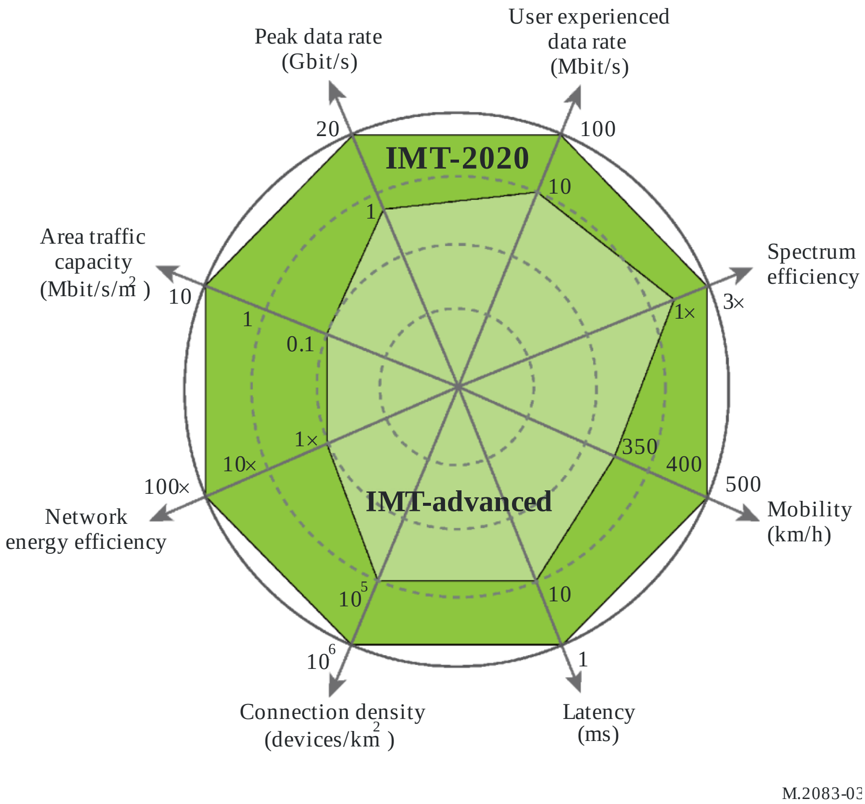


Figure 4 capabilities of 5G [13]

- **EMBB:**
  Regarding the peak data rate, we align with the peak data rate reported in [13], which specify 20Gbps for Downlink and 10Gbps for Uplink. Within descriptions of use cases, the term 'broadband' or occasionally eMBB is used to refer to both eMBB and user experience data rate (UDRAT). However, for clarity in our research report, 'broadband' requirements pertaining to individual device communications are attributed to UDRAT, while those pertaining to base stations or areas are associated with EMBB.

- **URLLC:**
  In the wireless access network segment, the latency is specified as 1 ms, as indicated in [13] Since the time required for end-to-end (E2E) communication and processing varies depending on the network topology and system configuration, a gap analysis will be conducted solely on cases

where the required distances for each use case are specified. This analysis will consider corresponding propagation times and the latency of the wireless access network segment. The time required for E2E transmission will be calculated using propagation speeds of 200,000 km/s for optical fiber and 300,000 km/s for wireless transmission.

- **MMTC:**
  Regarding the connection density, the density is set at 10^6 (device/km^2) ms as indicated in [13]

- **UDRAT:**
  Regarding the UDRAT while [13] specifies it as 100 Mbps, this value depends on the design policies of each Mobile Network Operator (MNO), and the actual capability of devices can exceed this limit. Therefore, as the threshold indicative of 5G capabilities, this research report defines following criteria, referring the maximum effective rates published by NTT DOCOMO [14], KDDI [15], and Softbank [16] (e.g., in Japan, the operators assigned 100MHz for sub6 and 400MHz for mmWave spectrums):
  - Downlink: 2.0Gbps
  - Uplink: 500Mbps

- **ACAP:**
  Regarding Area Traffic Capacity (ACAP), while [13] specifies it as 10 Mbps/km^2, this metric can vary depending on the design policies of each MNO, and the actual capabilities of devices may exceed this limit. Therefore, as a boundary value for 5G capabilities, it is set to 20 Gbps, similar to the EMBB detailed in [13]. Nevertheless, for use cases that specify area requirements per unit, a comparison with the 10 Mbps/km^2 limit will also be conducted to highlight the gap with MNO's design.

4 Use case requirements and gap analysis

In this chapter we will delve into the specific needs of our chosen 6G use cases and explore the potential integration of mWAD. Our aim is to uncover challenges and opportunities associated with mWAD technology within these diverse use cases. Our investigation will involve:

- *Thorough Analysis*: We'll carefully examine the technical requirements of each summarized use case, considering their unique communication needs and coverage demands.
- *Stakeholder Input*: Interviews with key stakeholders will provide valuable insights from those intimately involved in these use cases, offering real-world perspectives. Authors of this research report had a great support from NTT and KDDI subject matter experts to obtain their inputs on our findings.
- *Detailed Comparison*: We'll conduct a comprehensive comparative analysis, aligning the specific requirements of each 6G use case with the capabilities offered by mWAD. This systematic approach will help us identify areas of synergy and those requiring further adaptation.

Our objective is to gain a deep understanding of each use case and assess how mWAD technology can fit into these scenarios effectively. These insights are essential for the successful implementation/deployment of 6G networks. To concisely present our research findings, we will create summary for each SUC. We analyzed 170 6G use cases from 4 global documents, categorized them into 29 SUCs, and extracted 31 requirements as listed in Table 6. In the descriptions of each SUC, we introduce the requirement marked with **'*'** or 'x**'**. The '*' filled cells depict that we can find detailed requirements from the resources while the 'x' marked cells mean that we do not have much technical insights and details about that requirement/use case. The cells labeled with '-' mean that there is no specific requirement found for that use case.

Table 6 Summary of required capabilities for the summarized use cases of this report

SUC \ Capabilities	EMBB	URLLC	MMTC	UDRAT	SPCEF	MOB	ENEEF	ACAP	REL	SEC	COV	AI	POS	TSYN	NETMN	SENS	COMP	COST	IOT	DTWIN	WEARD	FSAFE	LOCC	ANOMD	UPDAT	EHARV	EUI	HOLO	XR	REMOP	AUTOP
3D Map *Creation/Maintenance	*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Agriculture/Fishing/Mining	*	*	*	–	–	–	*	*	x	x	*	–	*	–	–	x	–	–	x	x	–	–	–	–	–	–	–	–	*	*	x
Art/Design/Creative work	*	–	–	–	–	–	–	–	–	–	–	–	x	x	–	x	–	–	–	–	–	–	–	–	–	–	–	–	x	–	–
Autonomous/Assisted Drive	*	*	*	–	–	–	x	x	*	*	x	x	*	x	x	*	*	–	*	–	–	–	x	–	–	–	–	–	x	*	*
Cashless Payments	x	*	x	–	–	–	–	–	*	x	x	x	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Construction	*	*	*	–	–	–	x	–	x	x	–	x	*	x	–	*	–	–	x	x	–	–	–	–	–	–	–	–	*	x	x
Consumer Robot	x	x	x	–	–	–	x	–	–	–	*	*	x	–	*	x	–	x	–	–	–	–	–	–	–	–	–	–	–	*	–
Digital Divide Elimination	*	*	–	–	–	x	–	–	x	–	*	–	–	–	–	–	–	x	–	–	–	–	–	–	–	–	x	*	–	*	–
Education	*	*	–	–	–	*	–	–	*	*	x	x	*	–	*	x	x	–	–	x	x	–	*	–	–	–	–	*	*	*	–
Emergency/Disaster	*	*	*	–	–	–	*	–	*	x	*	–	–	–	–	–	–	*	–	–	–	–	–	–	–	x	–	–	x	–	x
Entertainment/Sports	*	*	*	x	–	*	x	x	*	x	*	*	x	x	–	*	–	–	–	x	x	–	*	–	–	–	–	x	*	*	–
Facility/Equipment Maintenance	*	*	x	*	–	*	x	–	*	*	–	x	x	x	–	x	–	–	x	x	–	–	–	–	–	–	–	–	–	x	*
Factory/Plant	*	*	x	x	x	–	x	x	*	*	*	*	*	*	*	*	x	x	x	x	–	x	*	–	–	*	–	–	*	*	*
Gaming	*	*	–	x	–	*	–	–	x	–	–	x	–	–	*	–	*	*	–	–	–	–	–	–	–	–	–	x	*	*	–
Government	x	x	x	–	–	–	–	–	x	x	x	–	–	–	x	–	–	–	–	–	–	–	–	–	–	–	x	–	–	–	–
Healthcare/Medical	*	*	*	–	–	–	x	–	*	*	*	*	*	*	–	*	–	x	*	x	*	–	–	–	x	*	*	*	*	*	*
Industrial Collaborative Robot	*	*	x	–	–	–	*	x	x	x	*	*	*	x	*	x	x	–	x	–	–	x	*	x	x	–	–	–	*	*	*
Insurance Service	–	–	–	–	–	–	–	–	*	x	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Personalized User Experience	*	*	–	–	–	–	x	–	–	x	–	x	x	–	–	–	*	–	*	–	–	–	–	–	–	–	–	*	*	*	*
Program Update	*	–	–	–	–	–	–	–	–	*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Real Estate Management	*	x	–	–	–	–	–	–	x	x	–	–	–	–	–	–	–	–	–	x	–	–	–	–	–	–	–	–	*	–	–
Restaurant	x	x	–	–	–	–	x	–	x	x	–	x	x	–	–	x	–	–	x	x	–	–	–	–	–	–	–	–	–	–	–
Smart City	*	*	*	–	–	–	*	–	*	*	–	x	–	–	*	–	–	–	*	x	–	–	*	–	–	–	–	–	–	*	*

Social Security/Surveillance	*	*	–	–	–	–	*	–	–	x	*	*	x	*	–	*	–	–	*	–	–	–	–	x	–	–	–	*	*	*	*
Space Life	x	–	–	–	–	–	x	–	x	x	*	–	–	–	–	–	–	–	–	x	–	–	–	–	–	–	–	–	–	*	*
Supply Chain/Product Life Cycle Management	*	*	x	–	–	–	x	–	x	*	*	*	x	*	*	*	–	*	*	x	–	–	–	–	–	x	–	*	*	*	*
Sustainable Life	x	x	x	–	–	–	x	–	x	*	x	–	x	–	–	*	–	–	x	–	–	–	–	–	–	–	–	–	–	–	x
Travel Navigation	*	*	x	–	–	–	x	–	*	–	–	–	x	*	–	x	*	–	–	x	–	–	–	–	–	–	–	–	*	–	–
Warehouse/Logistics	–	*	x	–	–	*	x	x	x	x	*	–	*	*	–	*	–	–	x	–	–	–	x	–	–	x	–	–	–	x	*

In addition, we list the documents where the correspondent use case is introduced. The documents are labeled with their short names as shown in Table 7.

Table 7 Abbreviations for investigated documents

Document	Short name
Next G Alliance Report, “6G Applications and Use Cases”	NEXTG
Hexa-X Deliverable D1.2**,** “Expanded 6G vision, use cases and societal values”	HEXAX
NGMN, “NGMN Use Cases and Analysis”	NGMN
B5GPC White paper**,** “Beyond 5G White paper –Message to the 2030s”	B5GPC

Continuing from our detailed analysis, we now delve into latency considerations in specific 6G use cases. By understanding the details of latency constraints and their alignment with 6G use cases, we aim to highlight the challenges and opportunities in integrating technologies like mWAD into next generation networks. There are diverse approaches to representing the low latency requirement. While some documents focus on the propagation time of radio access *(Physical layer latency)*, others refer it to the *end-to-end* time from application to application *(Application layer latency)*. Therefore, to make the scope clear, we adopt the definition provided by IOWN-GF [17]. IOWN-GF’s defined common workflows for the AI-Integrated Communications (AIC) use case are shown in Figure 5. It shows the common workflows and key requirements for AIC use cases. AIC use cases involve digitally recreating distant experiences to manipulate human senses. The primary requirement is to *manipulate human perception* by seamlessly transmitting experiences through the network. This necessity, detailed as the transmission date rate aspect, forms part of the essential requirements [17].

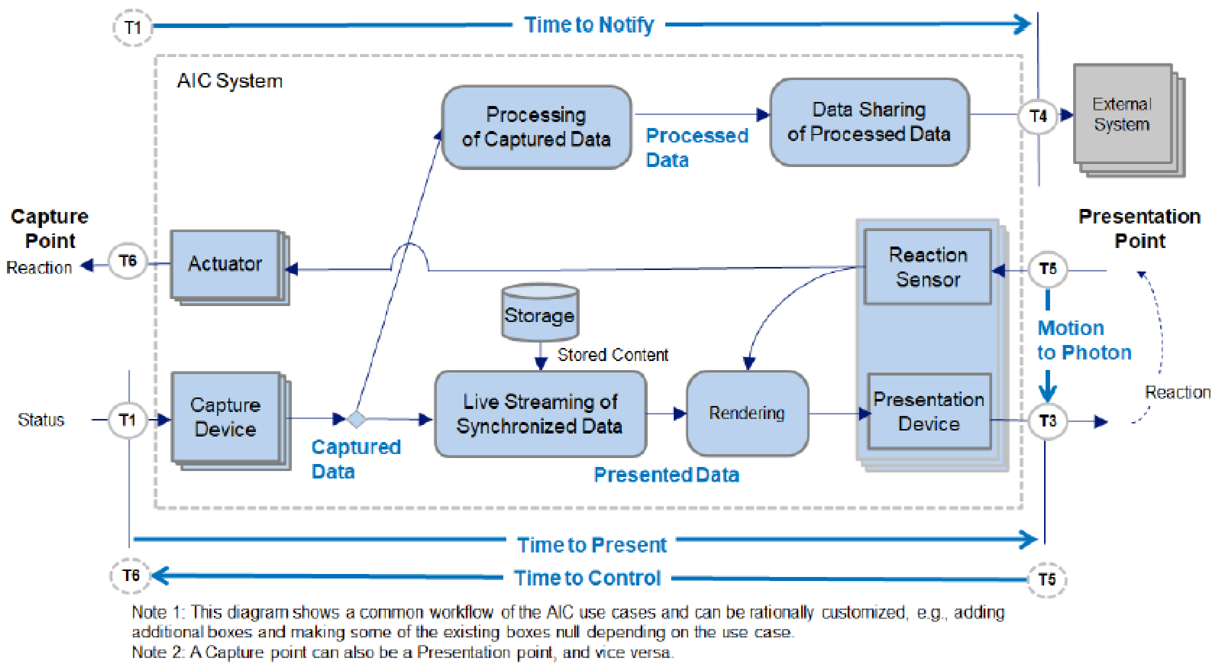


Figure 5 Common Workflows and key requirements for AIC use cases [17]

Cyber-Physical Systems (CPS) use cases involve sensing the physical world and replicating it in cyberspace using collected data. The key requirement is efficiently processing large amounts of data and quickly feeding it back into the physical world, referred to as the Data Volume aspect. Common workflows for the CPS use cases are shown in Figure 6 [18].

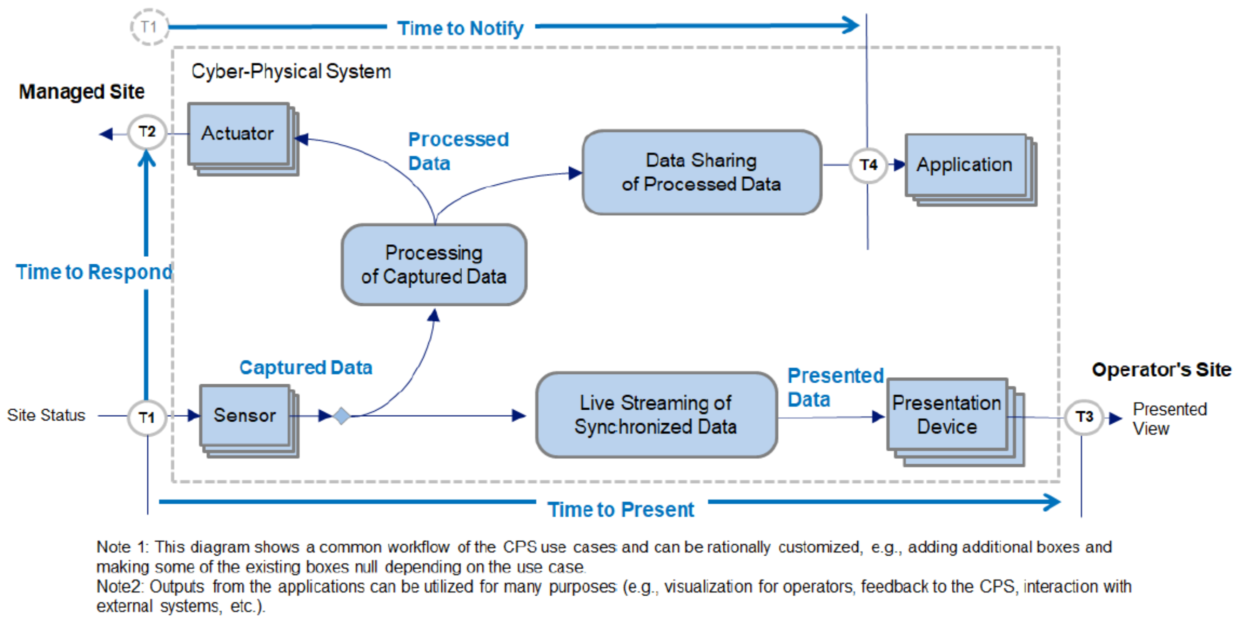


Figure 6 Common workflows and key requirements for CPS use cases.

Key requirements can be express along with the following workflows:

- **Time to Notify (TTN)** [Figure 5]: The E2E delay for Data Sharing (T1 to T4): “Processed Data” are made available to “External Systems” through “Data Sharing of Processed Data”.
- **Time to Present (TTP)** [Figure 5]: The E2E delay for “Remote Live Monitoring (T1 to T3): “Captured Data” are transferred to “Presentation Devices” in remote sites for remote live monitoring via “Live Streaming of Synchronized Data” and/or “Rendering”, which are used for the creation of enriched contents from multiple steams of “Captured Data”.
- **Motion to Photon (MTP)** [Figure 5]: The E2E delay for Motion to Photon (T5 to T3): The data captured by “Reaction Sensors” are reflected the presented view on the person’s “Presentation Device”, which provides, for example, a personalized view of a free viewpoint video.
- **Time to Control (TTC)** [Figure 5]: The E2E delay for Remote Control (T5 to T6): The data captured by “Reaction Sensors” are directly dispatched to “Actuators” at remote sites, which enables, for example, remote motion control of specific machines.
- **Time to Respond (TTR)** [Figure 6]: The E2E delay for quick feedback (T1 to T2): “Sensors” capture a physical space, the “Captured Data” is processed at

"Processing of Captured Data," and "Actuators" act upon the physical space according to the "Processed Data."

In the subsequent sections (from 4.1 to 4.29), we investigate the SUCs outlined in Table 5. Each SUC is comprehensively described based on the insights from whitepapers. Then its requirements, which have been marked with "*****", are highlighted based on available resources. It is important to note that certain requirements may not be explicitly specified due to lack of precise studies to date. Additionally, we bring some discussions around the gap analysis between existing technology and the specified requirements. Finally, we provide references for the readers seeking further exploration into each SUC.

4.1 3D Map Creation/Maintenance

A) *Description*:

For safety autonomous driving high-precision map is required. Because the moving area of the vehicles are not only flat street but also 3D structured high-way or in-building, the map shall have 3D data. In addition, the map shall be updated dynamically. To create and update of dynamic map vehicular sensor data, such as camera images and LiDAR (Light Defection And Ranging) data, will be utilized [11].

B) *Requirements*:

*This use case requires EMBB**.

- EMBB (including UDRAT):
  UPLINK: multi-10Gbps/cell [11]   UPLINK: 48 Gbps per building [18]
  UPLINK: from vehicle multi-Gbps/user [11]
  UPLINK: from cameras:45-60Mbps/fullHD@15fps [18]

C) *Gap Analysis*:

In 5G era, the target uplink peak data rate of 5G is 10Gbps. However, this use case requires Multi-10Gbps/cell or 48Gbps/building. The required data rate simply beyond the target uplink capability of 5G.

In addition, [11] mentioned vehicular sensor data will require multi-Gbps/user, if the data is aggregated to transmit from a vehicle, it also simply beyond the UDRAT capability of 500Mbps.

[18] mentioned the possibility of uploading data from infrastructure, such as shopping center. In that case, one camera requires uplink data rate of 45-60Mbps with full-HD and 15fps quality. A typical medium-size building with about 100 -150 tenants deploys 600-800 cameras [18]. To transmit such high uplink data rate, mmWave will be helpful. However, there are many walls, human body and other obstacles in the buildings. That will prevent efficient transmission of mmWave.

D) *Introduced in*:
B5GPC [11]

4.2 Agriculture/Fishing/Mining

A) *Description*:
Digital Twins (DT) for sustainable food production focus on achieving UN SDGs related to food security and sustainable agriculture. Embracing the concept of massive twinning, it addresses challenges posed by population growth, climate change, and the need for enhanced efficiencies. The primary focus is on providing increased network capacity to remote areas for real-time monitoring of micro-locations and optimized plant treatments. Leveraging synchronized digital representations of the physical world, this use case aims to enhance human expertise, enabling impactful decision-making and experimentation in the digital realm. Key to success is the fully synchronized digital representation, facilitating improved management and threat prevention in agricultural production. This use case emphasizes the transfer of large data volumes from underserved areas, underlining the importance of close synchronization to tackle sustainability, global coverage, and inclusion challenges [8].
On the other hands and based on the discussions around agricultural machinery category in [11], enabling skilled workers to provide remote instruction and support to new farmers, and formalization of the implicit knowledge of skilled workers and automation of pruning in accordance with the ambient environment are two important B5G/6G use cases that needs to be looked at.
Other application that can be achieved with B5G is remote control and automated operations in restricted access zone. To sustain the paper industry, efficient tree planting in remote, mountainous areas requires remote control and automated operations due to limited human access. Additionally, addressing resource depletion involves actively exploring offshore resources and developing mines [11].
Remote monitoring can be categorized as a use case in the smart agriculture initiatives of future agriculture and fisheries industry. Implementing smart agriculture with technologies like 5G involves trials with autonomous tractors and sensors for remote monitoring. The goal is reliable, high-speed, low-latency networks, crucial for fully automatic, driverless operations. Beyond 5G technologies, including broadband wireless access (BWA), are explored for achieving this. For effective implementation, farmers need to remotely monitor the vehicle and surroundings, with the low latency capabilities of 5G and Beyond 5G offering promising solutions for driverless agricultural systems [11].

B) *Requirements*:
This use case requires EMBB*/URLLC*/MMTC*/ENEEF*/ACAP*/REL/SEC/COV*/POS*/SENS/IOT/DTWIN/XR*/REMOP*/AUTOP.

- EMBB (including UDRAT):
  UPLINK: 280Mbps(8K/VR)
  UPLINK: >10Mbps /camera [19]
- URLLC: TTP<100ms [11]
- MMTC: 100,000/Cell (NB-IOT) [19]
- ENEEF: 10years Life [19]
- ACAP: 20dB Coverage Gain [19]
- COV: Rural, Undersea [8], [11]
- POS: Micro locations [8]
- XR: VR [11]
- REMOP: 8K video [11]

C) *Gap analysis*:
Field equipment uploads the 3D data including video stream and depth data to the server to be represented to the operator in the control room. Then required UPLINK bandwidth at the field is approximately 280Mbps/Unit. It means maximum 30 units in a cell are possible for current 5G capacity (as defined in section 3.3.3).
TTP < 100ms includes data compressing/uncompressing time. Therefore, acceptable overall propagation time is 45ms. It is possible depending on the optimized network integration.

D) *Introduced in*:
HEXAX [8], B5GPC [11]

4.3 Art/Design/Creative work

A) *Description*:
The 6G use case of Virtual Production aims to enhance content creation by fostering the creativity of creators and simplifying the production of entertainment content. Virtual production involves a novel camera technique that captures and merges the virtual space with the real subject, enabling the creation of high-quality video content without the need to be physically present at the location. In the context of B5G/6G communication, supporting content creators involves implementing wireless solutions, replacing traditional wired cables, to establish a highly flexible content creation environment. This innovation is poised to play a crucial role in shaping the future of content production [11].
Advancements in virtual production technology and AI-driven cloud-based video production workflows are anticipated to provide creators with the desired

value. Particularly in the social entertainment space, where entertainment and social interaction converge, content is becoming a bridge between creators and their audience. This evolution is driving the creation of hyper-personalized content tailored to specific individuals, further shaping the landscape of content production. [11].

B) *Requirements*:
This use case requires EMBB*/POS/TSYN/SENS/XR.

- EMBB (including UDRAT):
  UPLINK/DOWNLINK: 280Mbps (8K/VR).

C) *Gap analysis*:
This use case requires at least VR environment at each worker, it means 280Mbps for both UPLINK and DONWLINK direction. 5G can support this requirement. However, when we refer the Education use case, it is possibly happening that multiple students/trainees exist in a same area, in a school for example.
In addition, designers will use holograph for co-creation. The holograph requires 100Gbps per device. Current 5G allows 20Gbps and 10Gbps for DOWNLIN and UPLINK respectively. The required bandwidth will exceed the maximum capacity of current 5G.
(Please refer education use case to know the detailed information of holograph).

D) *Introduced in*:
B5GPC [11]

4.4 Autonomous/Assisted Drive

A) *Description*:
In the 6G technology, several compelling use cases emerge. Firstly, in the domain of "Support of Grand Operations," the integration of ultra-low latency, highly secure wireless communication facilitates automated driving and management of airport vehicles, as well as expedites aircraft maintenance through rapid data analysis. Secondly, advancements in air traffic control and aircraft sensors enable "Piloting Assistance and Operation Control," potentially reducing the need for multiple pilots through unmanned operations. Real-time data exchange between ground control and aircraft, particularly during adverse weather conditions, ensures safe navigation. Lastly, the proliferation of drones and flying vehicles, including taxis and emergency vehicles, necessitates precise positioning, advanced sensing capabilities, and robust communication infrastructure to ensure safe and efficient airspace navigation. These technologies collectively address challenges and enhance efficiency across

various sectors, promising significant advancements in the era of 6G connectivity [11].

In 6G era, several other promising use cases emerge, reshaping industries and augmenting capabilities. Autonomous driving stands at the forefront, leveraging advancements in remote control and autonomous operation to enhance safety and efficiency on the roads. Remote monitoring and control further extend this capability, facilitating tasks like remote operation of vehicles for various purposes, including mobility services and disaster response scenarios. These applications demand ultra-high transmission speeds of around 50 Gbps, minimal end-to-end communication delays of 1 millisecond, and exceptional reliability [11].

Collaborative perception and sensor fusion play a pivotal role in safety driving assistance, enabling vehicles to leverage both onboard sensor data and infrastructure-supplied information for enhanced environmental awareness. Meanwhile, distributed learning and inference, facilitated by the collaboration between multiple vehicles and base stations, tackle the increasing computational demands of advanced automated driving. By harnessing the collective intelligence of networked vehicles and edge clouds with AI capabilities, this approach ensures efficient processing and decision-making, paving the way for seamless integration of Beyond-5G technology and artificial intelligence in automated driving systems [11].

6G advances could also revolutionize remote monitoring of agricultural equipment, enhancing precision and efficiency. Integration of driverless tractors and sensors enables real-time crop assessment, ushering in a new era of automation and data-driven decision-making for increased productivity and sustainability in agriculture [11].

B) *Requirements*:

This use case requires EMBB*/URLLC*/MMTC*/ENEEF/ACAP/REL*/SEC*/COV/AI/POS*/TSYN/NETMN/SENS*/COMP*/IOT*/LCOC/XR/REMOP*/AUTOP*.

- EMBB (including UDRAT):
  Remote operation of work vehicle: Uplink 50Gbps [11]
  1Gbps/Vehicle, 12Gbps/Cell [18]
- URLLC: 1ms (E2E) [11]
  Automated Overtake TTR 10 ms [20]
  Pre-Crash Warning TTR 20 ms [20]
  See-Through Safety TTR 50 ms [20]
  Automated Unmanned Vehicle TTR 40-500 ms [21]
- MMTC: 120vehicles/km it means 12 vehicles/cell [18]
- REL: ≧99.9999 [11]
- SEC: Confidentiality, this use case might require the split of network ownership, network control, network transport and network security [8]

- POS: cms [11]
- SENS: cms [11]
- COMP: Edge computing [11]
- IOT: relying on external third-party sensors [8]
- REMOP: Unmanned Flight [11]
- AUTOP: autonomous vehicle [8], Automated driving, Unmanned Flight, Unmanned operations, self-driving tractors [11]

C) *Gap analysis*:
The remote-controlled vehicle upload data from vehicular sensors. The required uplink data rate is 50Gbps [11]. It simply exceeds the target UPLINK data rate of 10Gbps. In addition, the autonomous car requires UPLINK data rate 1Gbps/vehicle and 12Gbps/cell. 12Gbps of UPLINK data rate also exceeds the target UPLINK data rate of 5G.
In terms of ULRRC, “Automated cooperative driving for short distance grouping (CoSdG)” will require 1ms communication for End-to-End transmission in up to 200m. URLLC in 5G requires 1ms for wireless access network, therefore 1ms is impossible unless using direct End-to-End communications, such as side link. 1ms communication also requires no-retransmission.
In terms of SENS/POS, this use case requires cms accuracy. It is possible if <10cm is required by sensing capability of mmWave. However, it is impossible if 1cm is required. In that case, other kind of technic shall be used, such as high-resolution images.

D) *Introduced in*:
B5GPC [11]

4.5 Cashless Payments

A) *Description*:
In the context of 6G technology, the evolution of financial services is expected to undergo significant transformations. The digitalization of customer interactions, facilitated by the transition to online and cashless payments, will lead to the integration of various financial services and the development of new services in collaboration with other industries. The utilization of AI and big data will enhance operational efficiency, enabling the diversification of services such as credit analysis in financing and portfolio analysis in investment. The integration with other industries will be facilitated through Banking-as-a-Service (BaaS), where financial services can be embedded in applications across different sectors. Additionally, the emergence of digital currencies like e-money and cryptocurrency, including central bank digital currency (CBDC), is anticipated to redefine financial services beyond traditional offerings [11].

B) *Requirements*:
This use case requires EMBB/URLLC*/MMTC/REL*/SEC/COV/AI.

- URLLC: ≦ 2sec for transaction [13 MASTER]

- REL: Resilient network is required [11]

C) *Gap analysis*:
There is no significant gap on this use case.

D) *Introduced in*:
B5GPC [11]

4.6 Construction

A) *Description*:
In the realm of Construction and Real Estate, 6G technology revolutionizes maintenance and management practices by seamlessly integrating IoT into the infrastructure. Through the installation of sensors, various components such as buildings and infrastructure are continually monitored for factors like vibration, temperature, humidity, and gas levels, allowing for proactive and preventive maintenance [11].
Furthermore, 6G facilitates complete automation within the construction process. Autonomous construction machinery and robots take center stage, with self-driving vehicles transporting equipment and machinery efficiently. This automated ecosystem, supported by digital twins (DT) and B5G systems, ensures immediate responses to emerging issues, marking a significant leap in efficiency and responsiveness within the construction and real estate sectors [11].
The use case for construction machinery envisions significant advancements in automation, remote operation, and construction management. The primary objectives include the promotion of manpower saving and full automation, achieved through the integration of robot technology into construction machinery and the enhancement of automatic functions. Additionally, the application of remote construction machinery operation technology aims to address tasks that are challenging to automate fully. The future vision encompasses efficient operation and management with minimal operators, facilitated by the automatic operation of multiple construction machinery and optimized scheduling of remote operations [11].
Furthermore, the use case emphasizes safe and secure remote construction machinery operation accessible to anyone, featuring clean and safe operator rooms, intuitive interfaces for motion and sensory communication, and the implementation of low-latency, high-bandwidth communication networks with adaptive control based on network conditions [11].

B) *Requirements*:
This use case requires EMBB*/URLLC*/MMTC*/ENEEF/REL/SEC/AI/POS*/TSYN/SENS*/IOT/DTWIN/XR*/REMOP/AUTOP.

- EMBB (including UDRAT):
  Uplink/Downlink 20-40Mbps/device
  Uplink/Downlink 500Mbps/Floor

- URLLC: ≦100ms (TTC) [11]
- MMTC: 200 device/Floor
- POS: Positioning 1cm [11]
- SENS: Sensing 1mm
- XR: AR, VR

C) *Gap analysis*:
1cm of positioning accuracy exceeds the potential of mmWave sensing capability of a few cms. 1mm of sensing accuracy too. Therefore, other solutions, such as high-resolution image sensing, will be required.

D) *Introduced in*:
B5GPC [11]

4.7 Consumer Robot

A) *Description*:
In the 6G use case for electronics, particularly home appliances, B5G technology aims to seamlessly connect devices to users and environmental data. Key aspects involve achieving "health and comfort," "ease of use," and "energy saving" in home appliances. The integration of 6G functionalities, such as ultra-low latency, ultra-fast and large capacity, and ultra-massive connectivity, is crucial for these advancements.
Examples of B5G utilization include kitchen appliances with features like optimal ingredient selection, cooking safety monitoring, and real-time connectivity for decision-making. Home appliances benefit from functions aligned with user preferences, while air conditioning and heating equipment can be controlled for health-related factors, energy conservation, and overall environmental control. The overarching goal is to enhance user experience, energy efficiency, and the functionality of household appliances through the integration of Beyond 5G technology. [11].
Another notable application is the evolution of consumer robots into collaborative robots or "cobots." Moving beyond conventional automated devices like vacuum cleaners and lawn mowers, these future robots will play a vital role in everyday life. Enabled by 6G connectivity, these cobots will feature advanced capabilities such as video cameras for real-time processing on local servers, sophisticated sensing, and precise positioning for seamless interactions. The integration of connected AI in 6G will enable these robots to cooperate, collaborate, and assist in a situation-aware manner. This transformation is expected to lead to a surge in the number of devices, requiring higher capacity within home networks. The ultimate goal is to enhance the quality of life, allowing the elderly to stay comfortably in their homes for extended periods, showcasing the potential of 6G in supporting more complex scenarios and demanding connectivity needs. [8].

B) *Requirements*:
This use case requires EMBB/URLLC/MMTC/ENEEF/COV*/AI*/POS/ SENS*/COMP/IOT/EUI*/ AUTOP*.
- COV: Seamless connectivity across the network of networks [8]
- AI: menu Recommendation [11]
- SENS: Food condition, Environment, Air, and human condition [11]
- EUI: Universal UI [11]
- AUTOP: automated vacuum cleaners and lawn mowers [8]
  The handover process, to guarantee the required cycle times. [21]

C) *Gap analysis*:
There is no explicit requirement on this use case. To find the requirement and gap for mobile robot, you can find more information at use case 4.17 “Industrial collaborative robot”. That use case has stronger requirements to compare to “consumer robot”.

D) *Introduced in*:
HEXAX [8], B5GPC [11]

4.8 Digital divide elimination

A) *Description*:
A key use case in 6G is Coverage Expansion, which aims to extend communication services to traditionally unreachable areas for economic or technical reasons. This includes providing affordable communication globally, addressing coverage gaps, and contributing to UN Sustainable Development Goals. 6G envisions seamless continuity across terrestrial and non-terrestrial networks (NTN), offering 3D coverage spanning land, sea, sky, and space. Specific applications include optimal MBB coverage for remote areas, environmental monitoring using sensors, supporting unattended operations for economic growth, and ensuring uninterrupted services during natural disasters. The overarching objective is to establish a robust and inclusive communication infrastructure aligned with sustainable development goals [7].
The institutional coverage 6G use case aims to provide high-grade wireless services globally, with a practical focus on essential institutions in both developing and remote areas. This includes immersive communication like telepresence and remote education. To overcome challenges in deploying fiber communication, enhancements in 5G FWA with features such as 3GPP Release 16 IAB and 3GPP Release 17 NTN are utilized. The goal is to connect key societal institutions and fostering local connectivity. Anticipated advancements in 6G wireless backhaul capacity will make it cost-efficient to extend services even to currently prohibitive remote areas [8].
Another use case adopted from [9] is eliminating the North American digital divide. This 6G use case aims to eliminate the digital divide in North America, particularly focusing on people with physical disabilities. The digital divide,

characterized by disparities in broadband access speed, availability, competition, and adoption, is a significant challenge. The submission emphasizes "universal access" for individuals with disabilities, addressing both technical aspects like infrastructure quality and non-technical elements such as digital literacy and affordability. Bridging the digital gap involves recognizing the unique challenges faced by underrepresented populations, especially those with physical disabilities, and implementing comprehensive measures to ensure inclusive access to the internet.

B) *Requirements*:
This use case requires EMBB*/URLLC*/MOV/REL/COV*/COST/EUI/HOLO*/REMOP*.

- EMBB (including UDRAT):
  DOWNLINK: (8k*8K Visual Field) 2.35Gbps [17], (Holograph)100Gbps to 4.35Tbps/Dev from use case 4.9 “Education” requirements
- URLLC: sub-20ms, TTC+TTP: 5.5ms from Education requirements [17]
- COV: FWA, IAB, NTN, 100% @country [11]
- HOLO: telepresence, remote virtual education, and medicine [8]
- REMOP: Remote virtual education and medicine [8]

C) *Gap analysis*:
In terms of objectives of this use case, coverage is most important. And the requirement is 100% of each country. It is not yet achievable.
Other requirements such as EMBB/UDRAT and URLLC to be referred by each use case which can overlay on this use case: 4.15 “Government”, 4.16 “Healthcare/Medical”, 4.9 “Education”, accordingly.
As an instance, we refer the requirement from Education.
Downlink data rate of 2.35Gbps is achievable from the EMBB perspective. However, it exceeds the practical download UDRAT capability of 2Gbps. Based on [17] supposed student number in a cell is 100. Total download EMBB will be 235Gbps. It also exceeds the 5G EMBB of 20Gbps. Furthermore, when using holograph, it requires 100Gpbs – 4.35 Tbps/device, it extremely exceeds the 5G EMBB and UDRAT.

D) *Introduced in*:
NGMN [7], HEXAX [8], NEXTG [9]

4.9 Education

A) *Description*:
6G technology revolutionizes education by providing a fully immersive experience through XR headsets and motion sensors. This enables real-time interaction in cyber-physical classrooms, overcoming challenges of remote

learning. Digital twin technologies replace physical tools, while sensors capture gestures and movements, enhancing the overall experience. Universally accessible high-quality wireless networks ensure continuous service, allowing participation from any location, including remote or mobile areas. This innovation not only addresses pandemic-related challenges but also promotes inclusive education for students with disabilities [9].

Other prominent 6G use case is the enhancement of remote instruction and online communication. This advancement enables a more immersive and realistic transmission of an instructor's expertise, particularly in club activities and practical skills. Beyond traditional oral instruction, 6G facilitates the direct conveyance of sensations even in remote settings. This innovation proves especially beneficial for activities involving connectivity across distant locations, such as ensembles and choruses, fostering a heightened sense of collaboration and interaction among participants [11].

6G's hybrid class use case transforms education by seamlessly blending remote and in-person learning. Instructors can teach without disruption, transcending language barriers, creating a stress-free and inclusive educational environment [11].

B) *Requirements*:

This use case requires EMBB*/URLLC*/MOB*/REL*/SEC*/COV/AI/POS*/ NETMN/SENS/COMP/DTWIN/WEARD/LOCC*/HOLO*/XR*/REMOP*.

- EMBB (including UDRAT):
  DOWNLINK: (8k*8K Visual Field) 2.35Gbps [17],
  (Holograph)100Gbps to 4.35Tbps/Dev from Education requirements [17]
- URLLC: TTC: sub-20ms (wo/ Haptic), TTC+TTP: 5.5ms (w/ Haptic) [17]
- MOB: seamless, mobility between terrestrial and NTN networks [9]
- REL: ≧99.9999% [17]
- SEC: Very high sensitivity for user data privacy and network security. [9]
- POS: High accuracy localization and high-resolution positioning services. [9]
- NETMN: Multi-access operations should be enhanced to seamlessly leverage cellular and non-cellular communications [9]
- LOCC: sidelink, mesh, and multi-connectivity. [9]
- HOLO: Sports, music [11]
- XR: XR [9]
- REMOP: multi-sensory extended reality and AI/ML [9]

C) *Gap analysis*:

Downlink data rate of 2.35Gbps is achievable from the EMBB perspective. However, it exceeds the practical download UDRAT capability of 2Gbps. Based on [17] supposed student number in a cell is 100. Total download EMBB will be 235Gbps. It also exceeds the 5G EMBB of 20Gbps. Furthermore, when using holograph, it requires 100Gpbs – 4.35Tbps/device (a raw hologram with colors,

full parallax, and 30 fps will need up to 4.32 Tbps), it extremely exceeds the 5G EMBB and UDRAT.
In terms of URLLC, haptic needs 5.5 ms for TTC+TTP. 5G wireless access networks typically target 1 ms latency. When both instructor and student are using 5G wireless, it consumes 2ms for wireless access propagation. 3.5 ms allows 700km transmission without counting any computing and forwarding delay.

D) *Introduced in*:
NEXTG [9], B5GPC [11]

4.10 Emergency/Disaster

A) *Description*:
In the 6G technology, a key use case involves Remote Data Collection through the integration of Low Earth Orbit (LEO) satellites into NTN. This configuration, comprising LEO satellites, High Altitude Platforms (HAPs), and Unmanned Aerial Vehicles (UAVs), aims to address rural IoT connectivity challenges by supplementing terrestrial networks. The goal is to achieve global, ubiquitous mobile internet coverage for diverse devices. To ensure seamless integration, the satellite segment must align with terrestrial 6G networks in functional aspects such as interfaces, QoS, and security measures [9].
The implementation of coverage extension technologies involves communication with vehicles, roadside units, satellites, and HAPS. This application aims to secure communication channels for emergency vehicles in disaster scenarios. Additionally, it enables connected services beyond the traditional cellular network, extending support to ordinary privately owned cars, allowing them to make emergency calls even in areas outside typical coverage [11]. Universal coverage can be also achieved through the concurrent dissemination of personalized emergency bulletins, taking into account individual attributes, location, and specific situations [11]. A communication infrastructure in 6G ensures uninterrupted information exchange, irrespective of power supply concerns or service disruptions, particularly in the face of natural disasters [11].
Another 6G use case will be implementing a system that delivers notifications regarding the most efficient evacuation routes during disasters, characterized by ultra-fast and high capacity, unparalleled security, robust resilience, reliability, and autonomous functionality [11].

B) *Requirements*:
This use case requires EMBB*/URLLC*/MMTC*/ENEEF*/ REL*/SEC/COV*/ COST*/EHARV/XR/AUTOP.
- EMBB: UPLINK: 48 Gbps per building [18]
- URLLC: TTR: less than 100 msec [18]

TTN: less than 1 minute, e.g., for short-term predictions [18]
≦0.1ms (Radio access propagation) [22]

- MMTC: 100,000/km^2 [18]
- ENEEF: <1KW [18]
- REL: ≧ 99.99 [22]
- COV: A radius of several tens to hundreds of km [11]
- COST: Extreme, Low Cost [9]

C) *Gap analysis*:
UPLINK data rate 48Gbps exceeds the 5G target uplink data rate of 5G of 10Gbps. E2E (radio area) propagation time ≦0.1ms is ten times shorter than 5G target time (1ms). To achieve the 0.1ms propagation time, we need many restrictions and high-level environment to improve the radio quality. For example, distance to the antenna < 30km, no re-transmission, etc.

D) *Introduced in*:
NEXTG [9], B5GPC [11]

4.11 Entertainment/Sports

A) *Description*:
In the 6G immersive sports event use case, real-time motion capture technology and XR gaming revolutionize the viewing experience. The technology creates a dynamic representation of live games, allowing millions of global viewers to witness events from different angles. While traditional broadcasting suits most, 3D rendering offers a 360° view, personalized perspectives, and AI-assisted predictions of players' movements. This immersive experience extends to virtual interactions, enabling users to engage with friends while watching the game [8].
High-Speed Wireless Connection in Aerial Vehicle for Entertainment Service use case focuses on ensuring enhanced in-flight entertainment and services. Aimed at providing a seamless user experience in challenging environments, it addresses the limitations of existing solutions like NTN or NTN evolution for high-quality services on airplanes. A reliable in-flight wireless connection enables uninterrupted access to video streaming, gaming, and educational materials [9]. In one another 6G aviation use case, the focus is on ensuring safe, secure, convenient, and comfortable air travel experiences. The objective is to deliver passengers stress-free transportation by prioritizing safety and security measures while enhancing in-flight services to provide a comfortable journey [11].

Holographic communication is another highlight of 6G use cases. As content becomes more enriched, there is an anticipation for increasingly immersive media experiences, encompassing holographic communication and internet embodiment [11].

The metaverse's application in 6G technology extends to interactive live music experiences, fostering virtual interactions between artists and audiences. Utilizing volumetric capture technology, artists are brought into the virtual space in real-time, allowing audiences to participate in live events from any location with flexible viewpoints. B5G communications play a crucial role in enabling real-time connectivity for a large number of users in virtual space, facilitating shared enthusiasm and a heightened sense of unity for a more immersive entertainment experience [11].

B) *Requirements*:
This use case requires
EMBB*/URLLC*/MMTC*/UDRAT/MOB*/ENEEF/ACAP/REL*/SEC/COV*/AI*/POS/TSYN/SENS*/DTWIN/WEARD/LOCC*/HOLO/XR*/REMOP*.

- EMBB (including UDRAT): UPLINK: 14-230 Gbps per object (total ≦ 2 Tbps) for Live Sports/Music
  DOWNLINK: 48-200 Gbps [17]
- URLLC: MTP: 10 ms, TTP: 70 ms,
  interactive/synchronous components: ~10 msec@1000km [17]
- MMTC: ＞1,200,000 [11]
- MOB: high-speed wireless connection for and within an aerial vehicle [9], Flexible communication routing [11]
- REL: E2E DL/UL packet reliability is high. [9]
- COV: GEO, LEO, HAPS, ATG [11]
- AI: predict near future motion [8]
- SENS: biometric sensors [11]
- LOCC: Side link [9], in-flight communications [11]
- XR: XR [8], VR [9], Immersive AR/VR [11]
- REMOP: allows end users to experience the game from any angle with a 360° view [8].

C) *Gap analysis*:
This use case requires 230Gbps UPLINK data rate per object, totally 2Tbps. Data rate only for one object exceeds the 5G target UPLINK data rate of 10Gbps.
In terms of URLCC, [17] requires less than 10ms for interactive communication within 1,000km radius range. The propagation time on optical fiber for 1,000km, it requires 5ms. After adding the radio propagation time of 1ms the propagation time is 6ms. Therefore, to satisfy the required URLLC for interactive communication, the network and other equipment needs to finish all the required process within 4ms.

D) *Introduced in*:
HEXAX [8], NEXTG [9], B5GPC [11]

4.12 Facility/Equipment Maintenance

A) *Description*:

In the domain of facility and equipment maintenance within 6G technology, various use cases are envisioned. Smart maintenance is proposed for logistics and transportation, aiming to enhance operational efficiency. Additionally, in the railway sector, robotic support is considered for operational tasks [11]. Another aspect involves spatially and temporally flexible construction management within the machinery category, seeking to optimize construction processes [11].

In the context of machinery and agricultural machinery, 6G technology facilitates remote operation and management of automated agricultural machinery. Predictive maintenance strategies, including failure time prediction and efficient maintenance and repair of equipment failures, are also emphasized in this category [11]. Moreover, under the Electronics umbrella, the focus extends to heavy electric equipment, while precision electronics and semiconductors are highlighted in another facet, showcasing the broad applicability of 6G for maintaining and optimizing various equipment across different industries [11].

B) *Requirements*:

This use case requires: EMBB/URLLC/MMTC/ENEEF/REL/SEC*/AI/POS/TSYN/SENS/IOT/DTWIN/REMOP/AUTOP.

- SEC: Quantum encryption [11]

C) *Gap analysis*:

In terms of SEC, quantum encryption is not yet populated.

D) *Introduced in*:

B5GPC [11]

4.13 Factory/Plant

A) *Description*:

In the realm of 6G, DTs for manufacturing are evolving into Massive Twinning, enhancing production agility and efficiency. This involves real-time management of infrastructure resources, virtual testing of new products, and cooperative interactions among multiple DTs in flexible production processes [8].

The flexible manufacturing use case focuses on the growing trend of personalized and modular production, requiring robust wireless communication and localization services. With the rise of adaptable manufacturing systems and mobile robots, dynamic configuration of communication networks becomes crucial for each production task. This includes orchestrating Automated Guided Vehicles (AGVs) and implementing real-time communication services through a flexible framework. The use case extends industrial 5G capabilities, enhancing flexibility, self-organization, local processing, and direct communication in dense industrial environments [8].

Another key 6G use case involves deploying small, low-power micro-networks for manufacturing. A machine manufacturer intends to connect numerous sensors within their machinery using non-industrial, scientific, and medical spectrum for enhanced reliability. This entails employing low-power devices with limited coverage as an underlay network [8].

In the realm of Machining Equipment, the envisioned use cases for 6G and B5G technologies focus on enhancing factory operations through data-driven improvements, intelligent machining processes, and extensive sensor networks. One key application involves the automatic collection, sorting, and forwarding of processing data, facilitating more efficient data utilization. Another prospect envisions fully unmanned factories with the automatic generation of global machining plans, emphasizing increased automation and operational autonomy. Additionally, the advancement of the direct teaching method, achieved through safe interactions between humans and robots in virtual or augmented reality spaces, is highlighted as a significant use case. This innovation aims to enable direct teaching regardless of the operator's location, fostering a seamless and secure human-machine collaboration [11].

In the context of 6G application in smart factories for the manufacturing of daily necessities and cultural goods, several key capabilities are identified for B5G. Real-time monitoring of facility and equipment conditions relies on high-precision cameras. Additionally, the support of work processes through devices such as PCs, tablets, and VR/AR technology within manufacturing lines requires B5G capabilities like ultra-fast and large-capacity data transfer, ultra-low latency, ultra-low power consumption, and efficient positioning and sensing.

The advancement of factory automation and process automation in smart factories further underscores the need for B5G capabilities, including ultra-fast and large-capacity data handling, ultra-low latency, ultra-low power consumption, precise time synchronization, and advanced positioning and sensing technologies [8].

B) *Requirements*:

This use case requires EMBB*/URLLC*/MMTC/UDRAT/SPCEF/ENEEF/ACAP/REL*/SEC*/COV*/AI*/POS*/TSYN*/NETMN*/SENS*/COMP/COST/IOT/DTWIN/FSAFE/LOCC*/EHARV*/XR*/REMOP*/AUTOP*.

- EMBB (Including UDRAT):
  UPLINK: 10 Gbps per plant/factory [18]

UPLINK: 100Mbps/view [18], 2.35Gbps/drone or robot (8k) [18]
- URLLC: Sensor data flow, TTR: less than 2 ms, Time to Control + Time to Present: 10 msec (for haptic feedback) [18].
- REL: <10years [22]
- SEC: secure computing [18]
- COV: Service area (note) 50 m x 10 m x 10 m [22]
- AI: local compute capacities [8]
- POS: 5 cm (Vertical, Horizontal, Height) [18]
- TSYN: 10ps [23]
- NETMN: flexible, dynamic configuration of communication service [8]
- SENS: Video, Vibration [11]
- LOCC: direct communication, a large population of sensors in his machine using [8]
- EHARV: wireless power supply [18]
- XR: VR/AR [11]
- REMOP: real-time interaction with the physical world [8].
- AUTOP: Automation (PA/FA) [11]
- seamless inter-cell and inter-edge handover [18]

C) *Gap analysis*:
In terms of EMBB and URLLC, drone or mobile robot will require uplink data rate of 2.35Gbps for 8k video stream. It is less than 5G target uplink data rate of 10Gpbs. However, it exceeds the practical UDRAT capability of 500Mbps.
The UDRAT will require more than 100MHz bandwidth. It is possible when using higher frequency radio, such as mmWave or more.
It is better providing the network as one cell since hand-over is not preferable for drones and mobile robots. However, mmWave radio has limitation of transmission distance and penetration.
In terms of URLLC, this use case requires less than 2 ms for TTR. Considering the 1 ms radio access propagation time of 5G, the time allowed for other processing is only 1 ms. To achieve this requirement, eliminating the re-transmission at wireless network shall be essential.

D) *Introduced in*:
HEXAX [7], B5GPC [10]

4.14 Gaming

A) *Description*:
In the proposed 6G use case of mixed reality on gaming, participants engage in a collective virtual experience, seamlessly blending physical and digital elements. This shared space incorporates real and digitally enhanced objects, offering an immersive environment with synchronized sensory interactions.

The technology extends to digital meetings, allowing users to participate with holographic avatars and experience tactile feedback through smart contact lenses. Beyond gaming, it transforms remote work and training by simplifying digital co-creation. This vision aligns with ongoing developments in 3GPP Release 17, indicating a progressive move toward realizing this merged reality concept [8].

Drone racing emerges as a standout use case. Leveraging the advancements of the 5G wireless system, 6G aims to create a cyber-real racing environment with 2x16K resolution images displayed through a 360-degree interface. Drone racing's essence lies in image quality, heavily dependent on network capabilities. These advancements are set to elevate the drone racing industry by enabling full 3D imaging transmission at multi-Giga-bps range, offering a superior end user experience with precise space maneuvering and an exhilarating ultra-realistic interactive racing scenario [9].

The 6G use case of immersive gaming and entertainment focuses on meeting the growing demand for transformative gaming experiences. While 5G provides high-speed connectivity, 6G is deemed necessary to support an increasing number of geographically separated players with higher synchrony and low latency. Immersive gamers are willing to invest in premium equipment for superior quality. 6G's advantages include enhanced reliability crucial for immersive gambling, creating an environment where players feel physically present. QoE is paramount in cloud and XR gaming, and 6G offers real-time feedback for optimal QoE by bridging applications, devices, edge servers, and networks [9].

B) *Requirements*:

This use case requires EMBB*/URLLC*/UDRAT/MOB*/REL/AI/NETMN*/COMP*/COST*/HOLO/XR*/REMOP*.

- EMBB: (Including UDRAT):
  DOWNLINK: Raw data rate at the game user: 72 ~ 144 Gbps (8K, 120-fps) [17]
  Compressed data rate at the game user: 200 ~ 400 Mbps (8K, 120fps) [17]
- URLLC: MTP:10-600ms [17], < 20ms [8]
- MOB: (263km/h), Vehicular Speed [8], Vehicle Speed: 60 km/h = approx. 16.7 m/s [17]
- NETMN: AI capable self-management and adjustment of network resources [8]
- COMP: distributed collaborative computing [8]
- COST: play all low latency games on inexpensive terminals or without terminals [17]
- XR: XR [8]
- REMOP: better haptic feedback [8]

C) *Gap analysis*:
This use case requires 144Gbps at maximum when not compressing the image data. It exceeds the 5G target downlink data rate of 20Gbps. When we compress the image data it requires 400Mbps, it is achievable. However, the compression delay will suffer the MTP requirement of 10ms. It is tradeoff.

D) *Introduced in*:
HEXAX [8], NEXTG [8]
NOTE: B5GPC [10] introduces virtual sports, which is close to this use case.

4.15 Government

A) *Description*:
User-friendly UX is another 6G use case focuses on providing a user-friendly experience for accessing administrative services. It aims to ensure accessibility anytime and anywhere, regardless of user conditions or economic factors. The services will be available without geographic restrictions and in a safe and secure manner. Users will have stress-free access even during disasters, emergencies, or high communication traffic periods on their devices [10].

B) *Requirements*:
This use case requires EMBB/URLLC/MMTC/REL/SEC/COV/NETMN/EUI.

C) *Gap analysis*:
This use case does not have explicit detailed requirement.

D) *Introduced in*:
B5GPC [10]

4.16 Healthcare/Medical

A) *Description*:
In the 6G digital healthcare scenario, wearable devices monitor vital signs 24/7 for both healthy individuals and patients, transmitting data to the internet for analysis. This enables constant supervision, especially beneficial for the elderly. Advanced technologies like XR and haptic feedback enhance the immersive experience for medical staff, providing insights from digital twins. Wearable devices of the future will offer greater accuracy and reliability, serving diagnostic purposes within secure sub-networks connected to cloud repositories [7].
The E-Health for all Scenario use case utilizes cost-efficient 6G connectivity to extend advanced healthcare services globally, ensuring secure transmission

and compliance with regulatory standards. Services range from in-home consultations to remote expertise support for healthcare workers. Various scenarios cater to different regions and populations, including providing universal healthcare using low-cost devices and AI and implementing large-scale public health monitoring for disease prevention. Future healthcare systems may integrate technologies like sensor-based monitoring, XR, and drones to enhance remote healthcare delivery, anticipating increased demand by 2030. Mobile healthcare hubs like ambulances or mini-clinics may also play a role in providing state-of-the-art care wherever needed [8].

Untethered wearables and implants leveraging native 6G cellular connectivity offer autonomy and efficiency. Powered by low power 6G communications and chipsets, they outperform traditional connectivity technologies like Bluetooth and Wi-Fi [9].

In 6G, "In-Body Networks" revolutionize healthcare by enhancing wearable devices to monitor vital signs continuously. These devices, including surface sensors and implants, communicate with access points to transmit real-time health data for swift interventions. The integration of in-body sensing, and analytics enables interactive remote monitoring and predictive therapy, promising a significant shift in telemedicine [9].

6G technology also enables virtual clinical trials, revolutionizing drug development. By conducting trials online, geographic and time constraints are eliminated, allowing wider participation and faster data collection. Participants engage from home, with biometric sensors ensuring constant monitoring of vital signs [10].

6G technology can also revolutionizes remote surgery, enhancing minimally invasive procedures and enabling surgeries anywhere. Surgical assistant robots, coupled with advanced communication tech, offer high-resolution imaging and haptic feedback. Mobile surgery units ensure immediate response times [10].

6G technology can enable AI-based remote diagnosis, revolutionizing online medical care. With AI analyzing various data inputs like images and vital signs, diagnostics become real-time and location independent [10].

6G technology leverages medical treatment with minimally invasive procedures and targeted therapy. Ingestible devices like capsule endoscopes, equipped with treatment and drug delivery functions, enable direct intervention within the body without external incisions. Shrinking to nanomachines and micromachines, these tools conduct autonomous medical activities from diagnosis to treatment within the body, facilitated by real-time health management systems [10].

Another 6G use case features user-friendly pseudo-body robots with intuitive controls for operation by anyone. Enabled by global, low-latency, high-bandwidth communication networks, these robots ensure seamless performance across varying network conditions [10].

Medical devices are advancing in 6G to support and replicate sensory functions, extending beyond sight and hearing to encompass touch, taste, and smell. Research focuses on developing artificial skin sensors and wearable devices for transmitting tactile sensations. Integration with AR/VR and haptics technology enhances sensory interaction. Direct transmission of sensory information to the brain via Brain-Machine Interfaces (BMIs), such as Neuralink's implantable device, is a key focus. Ultra-security, resiliency, and reliability in communication technologies are essential for connecting sensors to BMIs. These devices must maintain continuous operation on a single charge with minimal power consumption for practicality [10].

B) *Requirements*:
This use case requires EMBB*/URLLC*/MMTC*/ENEEF/REL*/SEC*/COV*/AI*/POS*/TSYN*/SENS*/COST/IOT*/DTWIN/WEARD*/UPDAT/EHARV*/EUI*/HOLO*/XR*/REMOP*/AUTOP*.

- EMBB (including UDRAT): 68Mbps uplink for patient (8k video, compressed [10]) (remote diagnostics).
  280Mbps downlink for doctor (8k×2 video, compressed) [6], [9] (remote diagnostics)
  1Tbps/cell for data collection (Disease prevention) [18]
- URLLC: 10ms for haptics (TTC). [18]
  (1) Surgery robot in same room < 2ms [21],
  (2) Surgery robot remote operation < 20ms [21],
- MMTC: 1E+7 devices/km^2 (Disease prevention) [18]
- REL: Availability (1) 99.999999, (2) > 99.9999 [21],
  Reliability: MTFB (1) > 10 years, (2) > 1 year [21]
- SEC: physically and digitally secured, with any privacy and security breach [7] [7]
- COV: Body network [6], [7], [10], NTN [7], Building implant [9]
- AI: AI agent [7], false data filtering [18]
- POS: 1 cm [22]
- TSYN: 1 microsecond [22]
- SENS: biometric sensors [10], Body sensing [6]
- IOT: nano/micro machine [10]
- WAERD: nano device [10]
- EHARV: outdoor sensors: self-sustain power (e.g., solar) with battery backup up [10]
- EUI: Brain machine interface [10]
- HOLO: Perception [10]
- XR: XR tooling [6], AR [9] [10], VR, Haptics [10]
- REMOP: Haptic Information, enabling a paradigm of actuation such as medicine dispensers and pacemakers [6]., Virtual doctor [7], haptics [10]
- AUTOP: nano device [10]

C) *Gap analysis*:
The uplink data rate for remote diagnostics is achievable in 5G. However, disease prevention requires uplink data rate of 1Tbps/cell. It exceeds the target uplink peak data rate of 5G, which is 10Gbps.

D) *Introduced in*:
NGMN [6], HEXAX [7], NEXTG [9], B5GPC [10]

4.17 Industrial Collaborative Robot

A) *Description*:
In 6G era, enhanced machine communication is exemplified through two critical applications: the Robot Network Fabric and Interacting Cobots. The Robot Network Fabric envisions centralized traffic management for autonomous vehicles, drones, and AGVs in urban environments. By utilizing real-time data processing and path negotiation, this network can ensure safe and efficient navigation, potentially leading to the development of lighter and more cost-effective robots capable of innovative transport functions. Meanwhile, Interacting Cobots facilitate seamless collaboration between humans and robots, whether in industrial settings or as caregivers. By interpreting human actions and working alongside them on complex tasks, these cobots, empowered by advanced network controls, promise to enhance productivity and efficiency across various domains [6].
In the envisioned 6G use case of interacting mobile robots, machines autonomously coordinate tasks such as avoiding collisions and synchronizing movements. This extends into industrial settings with collaborative tasks and aerial drones. Key requirements include real-time data exchange, reliability, safety, low latency, and energy efficiency. It challenges 5G capabilities, prompting improvements in device density, latency, and local communication. 3GPP Release 17 aims to address these needs through time-sensitive communication, quality of service enhancements, and distributed AI functionality [8].
6G also enables online cooperative operation among service robots, enhancing industrial automation and daily life. Robots collaborate competitively with limited communication or cooperatively with seamless information sharing. This model improves coordination and productivity, highlighting the potential of advanced communication technologies in unstructured environments [7].
In 6G, online cooperative operation among service robots promises significant advancements in industrial automation and everyday life convenience. Leveraging AI-native communication fabric, 6G enables field robots to perform tasks in hazardous environments with real-time haptic feedback and reliable tele-operation. This convergence of communication, computing, control, localization, and sensing services ensures enhanced reliability, low latency,

and security, marking a paradigm shift in robotics applications empowered by 6G technology [8].

B) *Requirements*:

This use case requires EMBB*/URLLC*/MMTC/ENEEF*/ACAP/REL/SEC/COV*/AI*/POS*/TSYN/NETMN*/SENS/COMP/IOT/FSAFE/LCOC*/ANOMD/UPDAT/XR*/REMOP*/AUTOP*.

- EMBB (including UDRAT):
  (1) Robotic aided surgery, UPLINK: 2-16Mbps (HD camera) (UDRAT) for [21]
  (2) Collaborative carrying fragile robot, 2.5Mbps (UDRAT) [21]
  (3) Mobile robot > 10Mbps (UDRAT) [21]
  (4) Hazardous area remote operation, UPLINK: 68Mbps (8K Video) at hazardous area, DOWNLINK:280Mbps (8K/VR) at control room)
- URLLC: Video remote operation < 10-100ms, Haptics <2ms [21]
  (1) E2E: < 2ms (in same room), < 20ms (telesurgery) [21]
  (2) E2E: < 0.85-2.5ms [21].
  (3) E2E: < 1-50ms [21]
  (4) TTC: < 10ms for Haptic
- ENEEF: high-energy performance [7]
- COV:
  (1) in a room/telesurgery has no particular requirement [21]
  (2) 10m x 10m x 5m (local communication) [21]
  (3) <1km^2 [21]
  (4) 100m^2
- AI: Central Tasks of coordinating interacting entities to the entities themselves [7]
- POS: High precision in 3D [6]
- NETMN: Fully distributed configuration model for TSN [7]
- LOCC: high share of local communication [7], SL- Based [8]
  (2) Direct communication [21]
- XR: MR [8]
- REMOP: central coordination of robot trajectories, under the control of the network [6], Haptic feedback [8]
- AUTOP: a high number of autonomous mobile robots, drones, automatic guided vehicles (AGV) [6], autonomous robot [8]
- the handover process, to guarantee the required cycle times. [21]

C) *Gap analysis*:

In general, collaborative robot will work with other robots and humans. In many cases the robots need to avoid collisions and need to synchronize their action. Those use case does not require extremely high data rate. However,

collaborative robot in hazardous area will require XR and haptics capabilities. The possibly required bandwidth is achievable in 5G.
In terms of URLLC. The shortest requirement is less than 0.85ms. It is shorter than 5G target URLLC of 1ms. Therefore, no re-transmission at wireless access network is essential.

D) *Introduced in*:
NGMN [6], HEXAX [7], NEXTG [8].

4.18 Insurance Service

A) *Description*:
Another envisioned use case for 6G technology involves the implementation of highly secure networks, particularly beneficial for sectors like finance and healthcare. By integrating these secure networks into financial services, it aims to facilitate user-friendly yet highly secure transactions and operations within these critical sectors [11].

B) *Requirements*:
This use case requires REL*/SEC.
- REL: Resiliency [10]

C) *Gap analysis*:
There is no significant gap.

D) *Introduced in*:
B5GPC [10]

4.19 Personalized User Experience

A) *Description*:
In this 6G use case of a personalized hotel experience, advanced technologies enable seamless and personalized interactions for guests. Upon arrival, real-time tracking and intelligent sensors facilitate automated check-in processes, including facial recognition and personalized notifications to guests' devices. Throughout their stay, guests benefit from personalized services such as virtual concierge recommendations and automated room service provided by service robots. Importantly, the system prioritizes privacy by wiping clean any personal information from devices and resources once guests are no longer interacting with them, addressing security concerns associated with increased personalization in public settings like hotels [9].
Personalized shopping experiences in 6G era are poised to revolutionize the retail landscape. One notable use case involves the creation of immersive virtual stores where customers can engage in real-time shopping experiences,

interact with products, and even meet friends for shared shopping excursions. Leveraging predictive impact analytics, these virtual environments offer personalized features such as tailored sounds, scents, and digital mannequins displaying products based on individual preferences. Moreover, virtual sales consultants, equipped with customer-specific insights, guide shoppers through the virtual space, offering product recommendations and assistance. Additionally, immersive product demos and gamified retail experiences further enhance customer engagement and incentivize prolonged interaction within the virtual environment. With 6G’s capabilities, retailers can deepen their understanding of each customer, providing a highly personalized and interactive shopping journey [9].

B) *Requirements*:

This use case requires EMBB*/URLLC*/ENEEF/SEC/AI/POS/COMP*/IOT*/HOLO*/XR*/REMOP*/AUTOP*.

- EMBB (Including UDRAT): uncompressed video stream from capturing device 48-230Gbps/object [24]
- URLLC: TTN: less than 1 minute, TTP: 70 ms, MTP: 10 ms, TTC: 100ms [24]
- COMP: around 200 TFLOPS per application per building [24]
- IOT: Service, Robots, Sensors [8]
- HOLO: 360-degree product views, 3D visualizations [8]
- XR: AR [8]
- REMOP: Interaction with products [8]
- AUTOP: automated, personalized service robots [8]

C) *Gap analysis*:

When we look into the virtual shopping center, the service will be on the metaverse platform, which will require 360-degree product view. To realize that, uplink data rate of 40-230Gbps/object is required in uncompressed condition. It exceeds the practical 5G uplink capability of 500Mbps. However, such data stream is not so time conscious. Therefore, the video stream can be compressed in high rate. For example, H.266 compression can offer around 440:1 compression. It means 5G practical UDRAT and EMBB possibly satisfy this requirement.

D) *Introduced in*:

NEXTG [8]

4.20 Program Update

A) *Description*:

In the context of autonomous driving, vehicles undergo continuous enhancements even after deployment to bolster safety, cybersecurity, energy efficiency, and optimize route calculations. This improvement extends to updating essential datasets, such as the dynamic 4D maps, street-side conditions, and various pertinent information crucial not only for autonomous driving but also for navigation purposes. Ensuring the secure transmission of such critical data is paramount, given its direct correlation with safe driving practices [10].

B) *Requirements*:
This use case requires EMBB*/SEC*.
- EMBB (including UDRAT): DOWNLINK ≧ 1Mbps [22]
- SEC: Applying Quantum encrypted communications [11]

C) *Gap analysis*:
Quantum encryption Is not popular yet.

D) *Introduced in*:
B5GPC [10]

4.21 Real Estate Management

A) *Description*:
In the construction and real estate sectors, the advent of B5G technologies presents numerous potential applications. These include the utilization of digital twins for enhanced real estate management, trading, and investment, as well as the integration of VR for online property viewing. Additionally, advancements such as AI and the IoT will play pivotal roles, facilitating services like AI-driven investment advice and improving efficiency through IoT-enabled real estate management [11].

B) *Requirements*:
This use case requires EMBB*/URLLC/REL/SEC/DTWIN/XR*
- EMBB (including UDRAT): DOWNLINK/UPLINK 280Mbps(8K/VR)
- XR: VR [11]

C) *Gap analysis*:
To transmit 8K data and depth information from real estate filed requires uplink 280Mbps in addition to sensor data. 280Mbps uplink is possible. However, the consumed bandwidth is too much to support multiple points to maintain. For example, maximum 35 rooms in an apartment building for 10Gbps uplink EMBB.

D) *Introduced in*:
B5GPC [10]

4.22 Restaurant

A) *Description*:
In future restaurant settings, the widespread adoption of cooking and serving robots is anticipated to mitigate labor costs. These robots will rely on B5G capabilities, such as ultra-fast transmission of large image data with minimal delay, precise positional information, and advanced sensing abilities. Ultra-low power consumption is also crucial, particularly for serving robots, to enable prolonged autonomous operation. Overall, these advancements are poised to revolutionize restaurant operations, enhancing efficiency, and reducing reliance on human labor [11].
In preparation for unmanned restaurants, B5G technologies are expected to facilitate ultra-fast, low-latency networks crucial for operating serving and cooking robots efficiently. Emphasizing ultra-security and reliability, these advancements ensure safe and uninterrupted restaurant operations [11].

B) *Requirements*:
This use case requires EMBB/URLLC/ENEEF/REL/SEC/AI/POS/SENS/IOT/DTWIN.

C) *Gap analysis*:
For cooking robot or serving robot, you can refer the “Industrial Collaborative Robot” use case, which has similar requirements.

D) *Introduced in*:
B5GPC [10]

4.23 Smart City

A) *Description*:
The proposed 6G use case revolves around the concept of an immersive smart city, emphasizing the management and optimization of various parameters crucial for city livability, such as infrastructure, environment, healthcare, education, safety, and more. This entails addressing technical challenges related to data volume, traffic transfer, reliability, and real-time feedback. The use of DT technology emerges as a pivotal tool for mapping, planning, and operating future smart cities, allowing for the creation of dynamic models that replicate real-world scenarios. Through interactive 4D mapping, operators can forecast actions, manage activities, and schedule tasks efficiently, contributing

to the city's sustainability and transformation towards more sustainable models. This use case requires rapid data transfer and emphasizes the importance of sustainability and trustworthiness in meeting citizen demands and enhancing city livability [8].

IoT micro-networks is another 6G use case that involves creating IoT micro-networks in smart cities to manage tasks like energy, traffic, and safety efficiently. These networks use objects as relays to minimize energy consumption and avoid excessive base stations. Unlike 5G, 6G integrates micro-networks with different ownership and security management into wider networks, allowing for shared infrastructure and unified trust policies between private and public networks [8].

B) *Requirements*:

This use case requires EMBB*/URLLC*/MMTC*/ENEEF*/REL*/SEC*/AI/NETMN*/IOT*/DTWIN/LOCC*/REMOP*/AUTOP*.

- EMBB (including UDRAT):
  UPLINK: 48 Gbps/building, 45-60Mbps/surveillance camera [18]
  UPLINK: <800Gbps per km^2 for disaster notification (Sensor data) [18]
- URLLC: TTR: 10ms, TTP: 50ms [18]
- MMTC: 100,000 sensors per square km [18]
- ENEEF: 1kw/building [18]
- REL: 99.999 Availability frequency and voltage control [21]
- SEC: a private network with partly owned infrastructure and a private trust policy is integrated in a public network [8].
- NETMN: Self-adaptive [8]
- IOT: massive deployment of communicating objects. [8]
- LOCC: They need self-adaptive networks, relying on objects as relays. [8]
- REMOP: the control of the utilities (energy, water, gas, etc.), [8]
- AUTOP: automated train operations [8]

C) *Gap analysis*:

To achieve smart city, 3D or 4D map will be utilized. As introduced in use case 4.1 “3D Map creation”, a typical medium-size building with about 100-150 tenants would require 600 – 800 cameras. This means that the total image traffic would be in the region of 27-48 Gbps. It exceeds the 5G target UPLINK peak data rate of 10Gbps. Therefore, such building will be connected other network medium, such as optical fiber. UPLINK 64Mbps per video camera is possible but not easy for current 5G capability.

In terms of sensor data for disaster mortification, it will require up to 800Gbps per square km with the condition of 100,000 sensors. It exceeds the 5G target UPLINK peak data rate of 10G.

D) *Introduced in*:

HEXAX [7]

4.24 Social Security/Surveillance

A) *Description*:

In the future 6G scenario of automatic public security, wireless cameras will serve as universal sensors, aided by AI and machine vision to recognize people and objects while addressing privacy concerns. Additional sensing modalities like radio and acoustics will supplement data collection, allowing for advanced security screening procedures that eliminate traditional security lines. Radio sensing, facilitated by future communication systems, will play a key role in detecting potential threats such as metallic objects, enhancing overall security measures [8].

In 6G era, the public safety use case involves upgrading public safety applications with high-resolution video technology to enhance monitoring and response capabilities. By leveraging 6G, public safety entities can offer new services and potentially consolidate multiple services onto a single video stream, reducing costs and improving efficiency. This innovation presents a significant opportunity for cities to enhance public safety and streamline operations, ultimately leading to cost savings and improved services [9].

A new 6G use case targets safe and convenient air travel by optimizing transportation routes, enhancing security with advanced equipment like body scanners, and streamlining processes through facial recognition and biometrics at check-in and boarding gates. Additionally, it proposes automated navigation within airports using AR and personal mobility services, along with smart tags for efficient luggage management, reducing delays and enabling easy luggage tracing [11].

B) *Requirements*:

This use case requires EMBB*/URLLC*/ENEEF*/SEC/COV*/AI*/POS/TSYN*/SENS*/IOT*/ANOMD/HOLO*/XR*/REMOP*/AUTOP*.

- EMBB (including UDRAT): UPLINK:48 Gbps/building/45-60 Mbps/surveillance camera [18].
- URLLC: TTR: less than 100 msec, TTN: less than 1 minute [18]
- ENEEF: ≦1 KW/building [18].
- COV: Including Rural area [9]
- AI: gesture and action detection [7]
- TSYN: Hyper-high accuracy synchronization [7]
- SENS: Camera, Radio Sensing [8]
- IOT: a massive deployment of wireless cameras as sensors. [8]
- HOLO: ultra-high resolution imaging monitory systems [7]
- XR: AR-aided navigation [11]
- REMOP: remote operation platform systems [7]
- AUTOP: Platooning [11]

C) *Gap analysis*:
A typical medium-size building with about 100 -150 tenants would require 600 – 800 cameras. This means that the total image traffic would be in the region of 27-48 Gbps. It exceeds the 5G target uplink peak data rate of 10Gbps. Therefore, such building will be connected other network medium, such as optical fiber.

D) *Introduced in*:
NGMN [6], HEXAX [7], NEXTG [8], B5GPC [10]

4.25 Space Life

A) *Description*:
The envisioned 6G use case involves leveraging B5G communication technologies to integrate outer space and cyberspace with terrestrial activities, thereby extending the scope of human endeavors. This integration aims to treat outer space and cyberspace as seamless extensions of human life activities, enabling bidirectional projection and synchronization between these realms and ground-based operations. Such advancements are anticipated to facilitate space activities without significant delays by synchronizing outer space and ground activities in cyberspace, marking a transformative shift in how humans engage with these domains [11].

B) *Requirements*:
This use case requires EMBB/ENEEF/REL/SEC/COV*/DTWIN/REMOP*/AUTOP*.
- COV: NTN [11]
- REMOP: Remote medical care [11]
- AUTOP: NTN operation [11]

C) *Gap analysis*:
It can refer use case 4.16 “Health care/Medical”, since this use case requires remote medical care for human in the space.
For this use case, the NTN is essential. However, NTN is emerging technology. Maturation is required for cost efficiency and dependability.

D) *Introduced in*:
B5GPC [10]

4.26 Supply Chain/Product Life Cycle Management

A) *Description*:
In the proposed 6G-enabled “Smart Industry” use case, mobile communication technologies drive a holistic approach to production, emphasizing sustainability

and efficiency. Utilizing interactive mapping, mixed reality co-design, and advanced manufacturing, processes are streamlined from research to delivery, reducing time-to-market and enhancing product quality. Motion control automation ensures precise manufacturing, while biodegradable tags and cellular systems optimize shipping and delivery, promoting resource circularity and efficiency [7].

6G will revolutionize logistics with autonomous supply chains, employing AI agents to automate every step from planning to delivery, adapting to unforeseen events. Enabled by micro tags and global connectivity, comprehensive lifecycle tracking of goods enhances efficiency and reduces resource consumption. Integrated with flexible manufacturing, the supply chain becomes dynamic, catering to diverse resource demands. This transformation requires seamless integration of technologies to orchestrate optimal supply chains while ensuring continuous monitoring for responsiveness and dynamic adjustments, promising streamlined and efficient logistics [8].

In the 6G era, several key use cases are emerging to address various industry needs. One such use case involves Industrial Product Lifecycle Management, which focuses on managing the entire lifecycle of industrial products to promote sustainability. This includes implementing systems for total amount indicator management in processes like mining, separating, and refining rare earths, thereby ensuring traceability and responsible resource management. Another notable application is Labor-saving in Supply Chain Control and Development Sites within the semiconductor industry, aiming to streamline processes and reduce manual intervention, thereby improving efficiency. Additionally, ICT Integration in Traditional Sales is transforming traditional retail operations by shifting towards virtual stores, enhancing sales projections accuracy, optimizing supply chain logistics, and leveraging technologies such as display robots to mitigate labor shortages. These use cases collectively represent the diverse applications of 6G technology across various sectors, emphasizing enhanced efficiency, sustainability, and innovation in industrial practices [11].

B) *Requirements*:

This use case requires EMBB*/URLLC*/MMTC/ENEEF/REL/SEC*/COV*/AI*/POS/TSYN*/NETMN*/SENS*/COST*/IOT*/DTWIN/EHARV/HOLO*/XR*/REMOP*/AUTOP*.

- EMBB (including UDRAT): Downlink: 280Mbps (8K/VR) for co-design.
- URCCL: (10ms for haptic remote operation platform)
- SEC: trusted data [11]
- COV: NTN, IAB [8]
- AI: Virtual Store, Sales prediction [11]
- TSYN: Motion Control [7]
- NETMN: Motion Control [7]
- SENS: Integrated Sensing [7]

- COST: cost-efficient access [8]
- IOT: Narrowband Internet of Things [8]
- HOLO: Ultra-high-resolution imaging [7]
- XR: Mixed reality co-design [8]
- REMOP: remote operation platform [8]
- AUTOP: display robot [11]

C) *Gap analysis*:
This use case includes all the activities through the product life cycle. Including R&D, Design, Manufacturing, Sales, Logistics, and Maintenance.
R&D and Design is covered by Art/Creative work use case. Manufacturing and Logistics are covered in Smart Factory/Plant and Warehouse/Logistics use case respectively. Above mentioned requirements are converged requirements of them. There is no significant gap from 5G.

D) *Introduced in*:
NGMN [6], HEXAX [7], B5GPC [10]

4.27 Sustainable Life

A) *Description*:
The envisioned 6G network promises a transformative impact across various sectors, particularly addressing the challenges and opportunities highlighted by the COVID-19 pandemic. Under the first theme of “Use of ICT due to COVID-19,” several key use cases emerge. Customer flow management and analysis, coupled with temperature measurements at entry points, are poised to enhance safety and efficiency in retail environments. IoT technology further aids in avoiding congestion and optimizing resource allocation. Concurrently, the pandemic has accelerated the expansion of online supermarkets, leveraging digital platforms to meet consumer demands while mitigating health risks. Additionally, sharing-based delivery services emerge as a novel approach, fostering collaborative consumption models to streamline logistics and reduce environmental impact. Under the “Shift to digital services,” the focus shifts towards enhancing digital engagement and convenience. Support for social media integration and novel purchasing methods, such as through internet and smartphones, promises to redefine customer experiences and interactions with businesses. Moreover, the provision of value-added services alongside product offerings seeks to deepen consumer engagement and loyalty in the digital marketplace. Finally, under the “Consumption and sharing” umbrella, emphasis is placed on redefining the value proposition of products and goods. Beyond their initial purchase, products hold inherent value through consumption and sharing. This perspective underscores the potential for novel

business models centered around circular economies and collaborative consumption, shaping a more sustainable and interconnected future [11].
In 6G and in the domain of food delivery services, drones are envisioned to revolutionize the industry by enabling home meal deliveries with unprecedented efficiency and speed. These drones, operating at Level 4 capability, necessitate ultra-fast and large-capacity connectivity, ultra-low latency, and robust security measures to ensure smooth flight over urban areas. To extend flight duration, minimal energy consumption is paramount, alongside advanced positioning and sensing functionalities to navigate intricate flight paths. Moreover, considerations for coverage expansion are crucial, particularly for reaching remote or challenging terrain. In another use case, the expansion of personal mobility and infrastructure systems is poised to transform society, enabling enhanced remote work, and addressing population-related challenges. Through ultra-fast connectivity, low latency, and autonomy, this advancement promises to foster improved mobility solutions and high-quality remote-control systems, contributing to a more connected and efficient future [11].

B) *Requirements*:
This use case requires EMBB/URLLC/MMTC/ENEEF/REL/SEC*/COV/POS/SENS*/IOT/AUTOP.
- SEC: Trusted Network, Data for digital service [11]
- SENS: biometric sensors for remote health management [11]

C) *Gap analysis*:
This use case includes helping the people who has difficulty for mobility, shopping, healthcare, etc. by the reasons of rural area, older people, diseases like COVID-19. This use case is generalized one. Concrete requirements are represented in appropriate dedicated use case.
Food delivery by drone and personal mobility are represented in use case 4.4 “Autonomous/assisted drive” use case.
Healthcare is represented in use case 4.16 “Healthcare/Medical”.
Shopping is represented in use case 4.19 “Personalized User Experience” which includes virtual shopping center.

Introduced in:
B5GPC [10]

4.28 Travel Navigation

A) *Description*:
The AR navigation use case for 6G integration emphasizes merging entertainment and social interaction, particularly in tourism applications. With

AR glasses, users can access real-time travel information overlaid onto physical locations, enhancing their understanding and experience. This integration allows for seamless interaction between virtual and physical spaces, enabling intuitive access to information. Additionally, it facilitates location-based gaming and social interaction, creating novel experiences. This use case relies on advanced information processing, such as digital twins, and requires a network capable of end-to-end communication to support the flow of data from capturing physical environments to mapping virtual information back onto physical spaces [11].

B) *Requirements*:
This use case requires EMBB*/URLLC*/MMTC/ENEEF/REL*/POS/TSYN*/SENS/COMP*/DTWIN/XR*.

- EMBB (including UDRAT):
  DOWNLINK:4~8 Gbps/XR dev. (Virtual travel) [17]
  UPLINK:120Mbps/XR dev. (onsite) [17]
- URLLC: TTP 16ms – 33ms for 60fps and 30fps AR navigation [17]
- REL: 0.999999 [17]
- TSYN: 1 ms jitter [17]
- COMP: Cloud/Split rendering [11]
- XR: AR navigation [11]

C) *Gap analysis*:
For sight-seeing, the view spot is replicated on cyber space by uploading sensor data and captured image data. A traveling person will ware XR goggle and image capturing (video) camera. DOWNLINK data rate of 8Gbps exceeds the practical 5G downlink UDRAT capability of 2Gbps.

D) *Introduced in*:
B5GPC [10]

4.29 Warehouse/Logistics

A) *Description*:
The integration of Beyond 5G technologies into warehousing and logistics operations promises transformative benefits. In one use case, B5G IoT systems offer a sophisticated solution for tracking and managing the location of packages through the deployment of RF tags and advanced IoT technologies. This enables real-time monitoring and efficient management of inventory, enhancing overall logistics efficiency. The second use case focuses on the automatic operation of machines and robots within warehouse and distribution facilities. By leveraging B5G local communication networks, seamless communication is ensured, facilitating the automatic operation of machinery and robots. Moreover, the monitoring of interactions between

individuals, machines, and robots helps prevent accidents, ensuring a safe working environment. Additionally, the digitalization and automation of port operations, referred to as “cyber ports,” streamline port activities, optimizing throughput and enhancing overall logistics operations. These applications collectively illustrate the potential of B5G technologies to revolutionize warehousing and logistics, ushering in a new era of efficiency and safety [11].

Another 6G logistics use case focuses on revolutionizing transportation efficiency, leveraging drones, autonomous vehicles, and high-speed modes like railways and drones for swift deliveries. It also emphasizes automated maintenance, high-volume transportation through platooning, and integration with next-gen mobility solutions like unmanned taxis. This vision aligns with use case 4.23 “Smart City” initiatives, aiming for streamlined operations and mass transportation [11].

Other potential use case of 6G technology involves enhancing port operations. This includes automating tasks such as operating port cranes remotely and using robots for loading and unloading cargo, which reduces the need for manpower. Additionally, in-port transportation vehicles can be driven autonomously, and cargo vehicles can be precisely parked using automation. Moreover, the efficiency of navigation can be improved through the utilization of ship data, facilitated by a fleet operation center [11].

Another use case revolves around monitoring maritime navigation and the marine environment. This entails automating operations to enhance navigation efficiency by leveraging ship data within a fleet operation center. Furthermore, the use of radio-controlled undersea drones allows for monitoring both the external and undersea environment of vessels, contributing to better navigation and environmental awareness [11].

B) *Requirements*:

This use case requires URLLC*/MMTC/MOB*/ENEEF/ACAP/REL/SEC/COV*/POS*/TSYN*/SENS*/IOT/LOCC/EHARV/REMOP/AUTOP*.

- URLLC: ≦1ms @local [22]
- MOB: < 30 km/h for inbound logistics [22]
- COV: Oversea, undersea [11]
- POS: 1cm [22], < 10cm for cargo loading [11], < 20cm(H) for inbound logistics [21]
- TSYN: 1ms [22]
- SENS: Undersea sensing [11]
- AUTOP: Ship, Drone, Crane, Track [11]

C) *Gap analysis*:

Position requirement is less than 1cm, that is impossible for 5G technologies. Even when using mmWave offers several cm accuracies for sensing/positioning. Considering the 5G target URLLC of 1ms for wireless

access, 1ms for local communication is a big challenge even for side-link. Re-transmission shall be eliminated.
Oversea and undersea coverage is also big challenge.

D) *Introduced in*:
B5GPC [10]

5 Considerations

In this chapter, our focus shifts to higher-layer view of Step 6 of our methodology (see section 2.1), where we carefully examine the disparities between the requirements and gaps we've identified in Chapter 4 and the technologies currently available. The primary goal is to analyze through a cross sectional view the gaps and challenges limiting the seamless integration of mWAD into the selected 6G use cases. For this purpose, we go through below approaches:

- *Comparative evaluation*: We conduct an in-depth comparison between the detailed requirements of our selected use cases and the specifications offered by existing technologies. This analysis helps us identify areas where current solutions do not align perfectly with the specific demands of our 6G use cases.
- *Feasibility analysis*: We conduct a thorough assessment to see if it's practical to bridge the identified gaps. This includes examining possible changes to current technologies and considering new methods that could effectively resolve the differences.

Many of the identified gaps pertain to bandwidth and latency. Figure 7 illustrates the maximum downlink data rates per device across different use cases, while Figure 8 shows the maximum uplink data rates per device. The orange dashed line represents the predefined boundary value, as defined in section 3.3.3. Many instances exceeding this boundary value are related to the transmission of high-resolution images and VR images required for immersive experiences. For example, the utilization of holography necessitates a maximum downlink bandwidth of 100 Gbps.

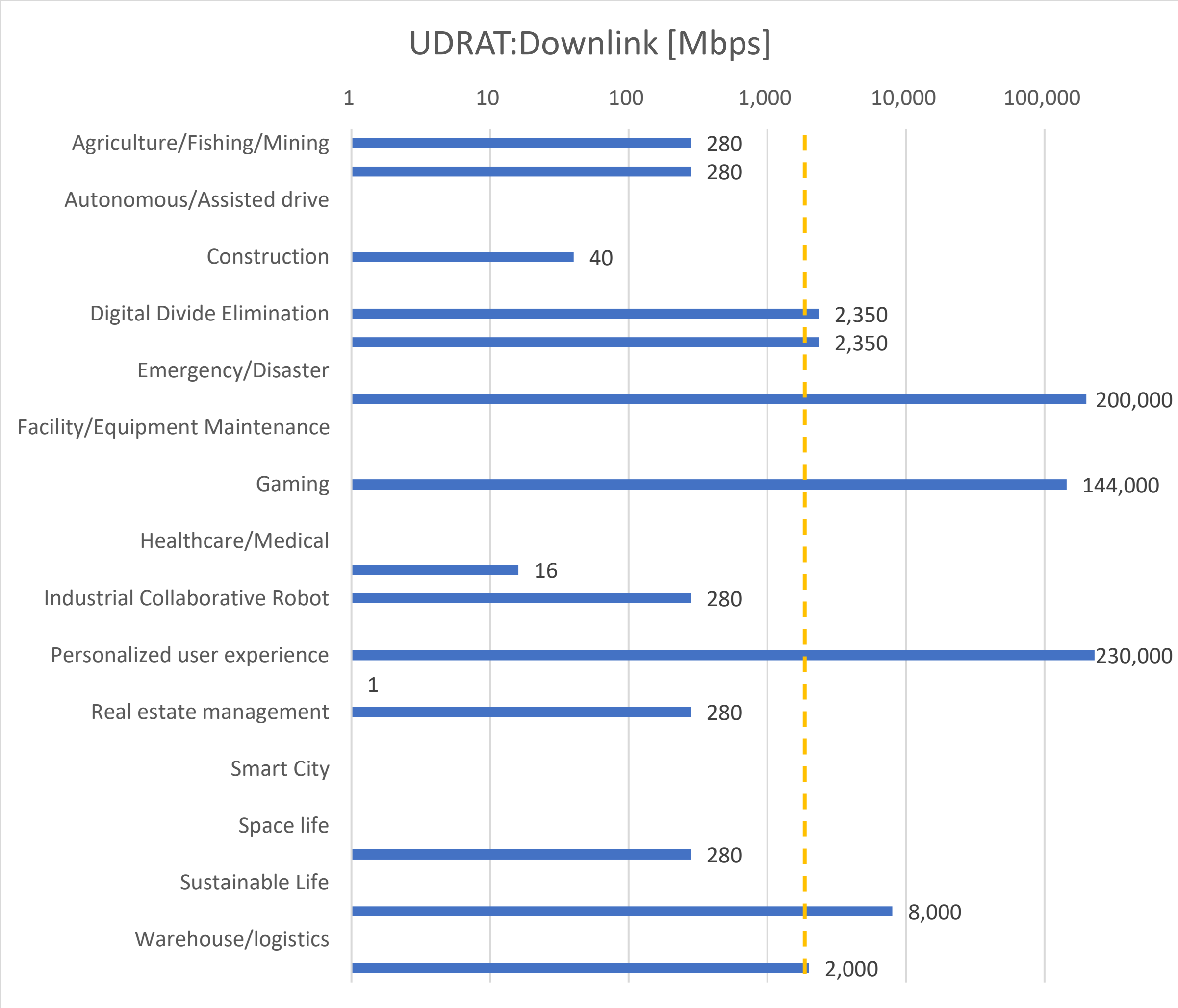


Figure 7 Required downlink data rate per device

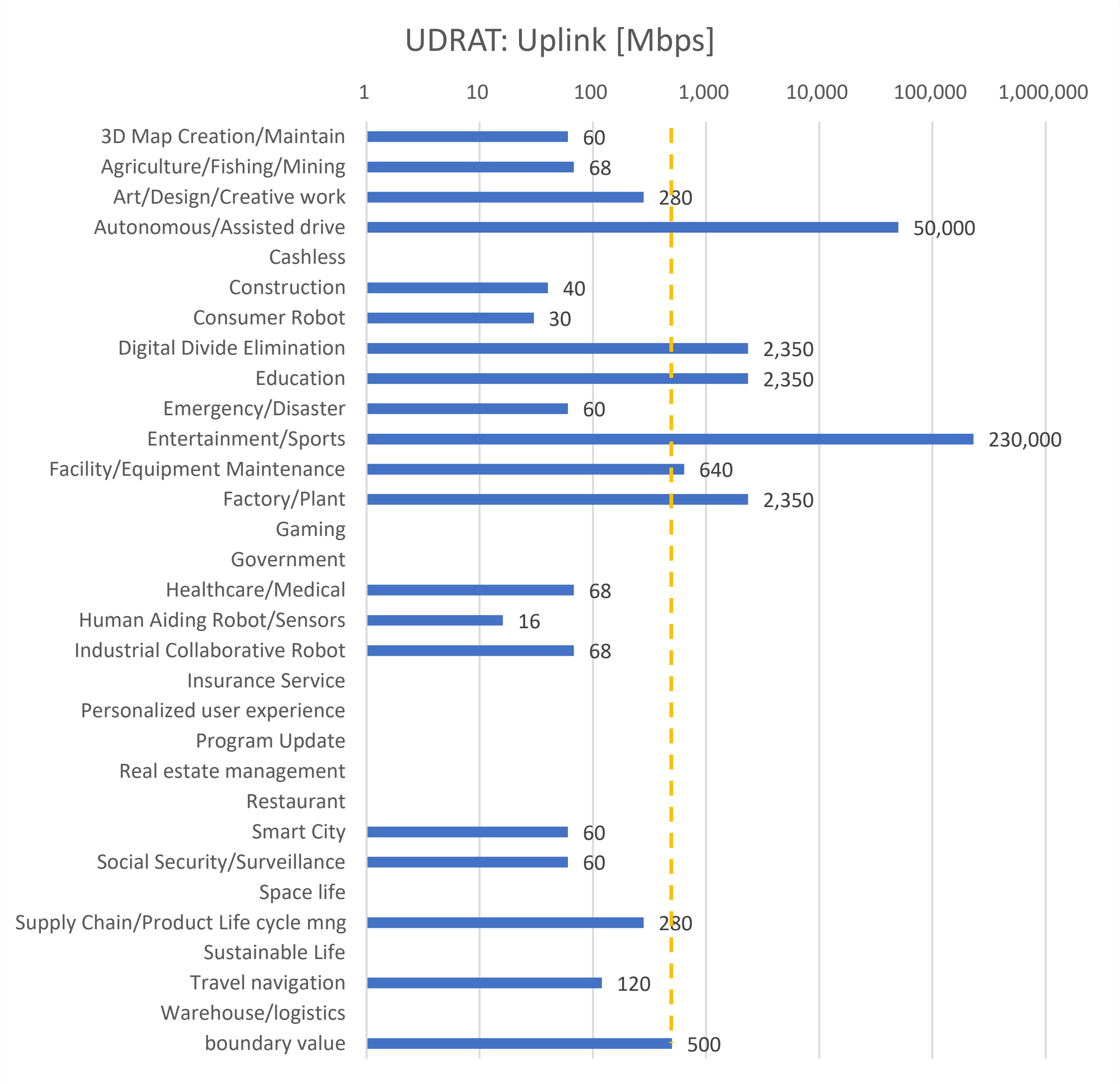


Figure 8 Required uplink data rate per device

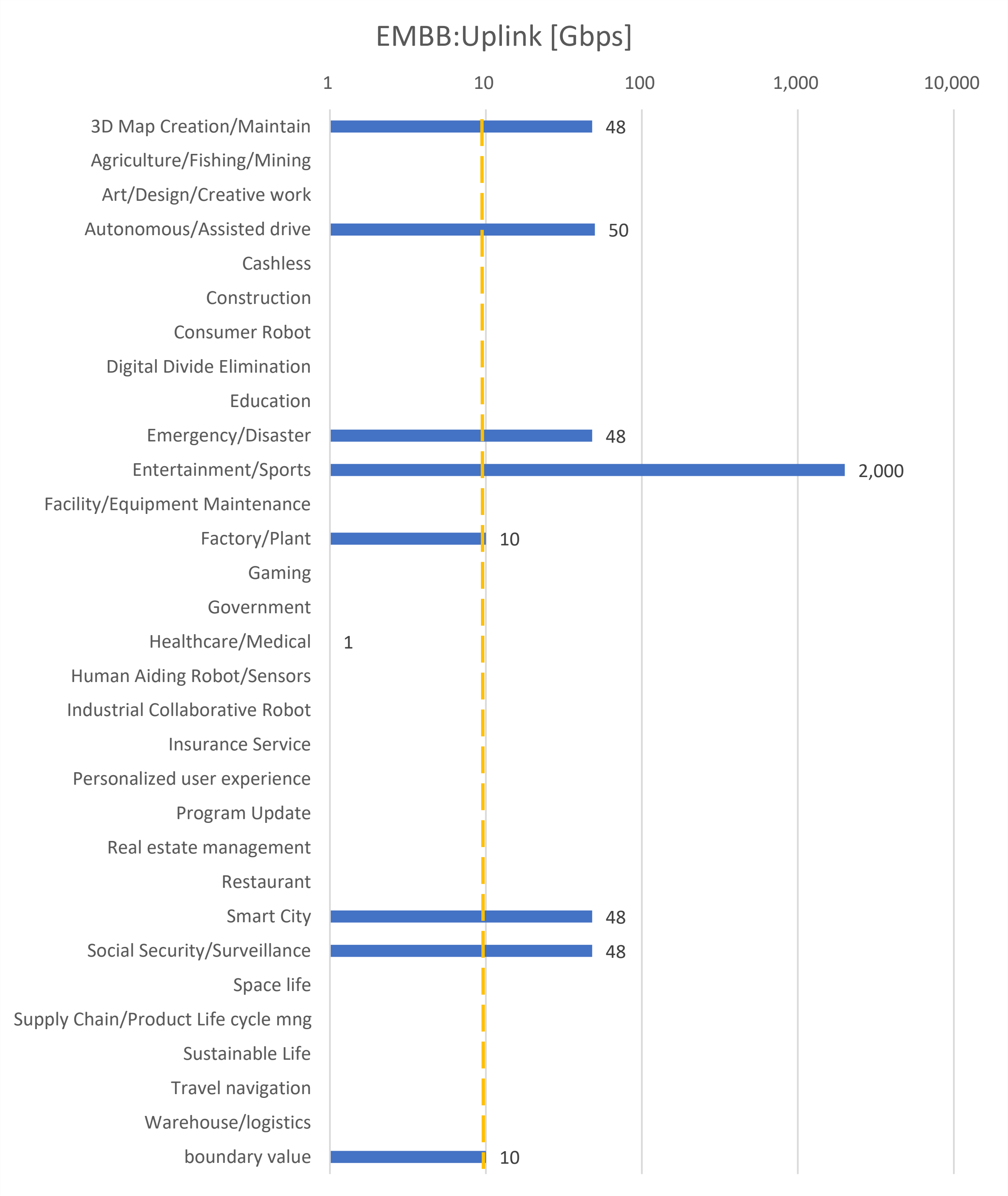


Figure 9 Required uplink data rate per cell.

In Figure 7 to Figure 9, a significant gap is observed in the uplink data rates, notably observed in both EMBB and UDRAT, each showing gaps in six use cases. To enhance the data rate of UDRAT, the following measures can be considered:

A) Utilizing wider frequency bandwidth:

Expanding radio resources can lead to an improvement in data rates. While there are differences between countries, mmWave typically offers greater bandwidth than Sub6, making its utilization a key. For instance, in Japan, while 100 MHz is allocated to Sub6, 400 MHz is allocated to mmWave, offering four times the bandwidth. Full utilization of these allocated resources is crucial. Furthermore, the allocation of new bands directly increases communication resources, which is highly effective. Discussions regarding new frequency allocations were also conducted at World Radiocommunication Conference 2023 (WRC-23) [25].

B) Using higher order modulation schemes:

Using the same radio resources to transmit more data can enhance the data rate itself.

C) Reducing the number of UE assignments per MIMO layer:

It is self-evident that reducing the number of UEs sharing a given bandwidth increases the allocation of data rates per device. This reduction guarantees fair data rate allocation to individual devices, thereby improving network performance and user experience.

D) Changing the TDD ratio:

Semi-synchronous methods used in Local 5G, which can change uplink and downlink rates based on resource requirements, are an option, but they are limited to the distribution of predetermined resources. Therefore, there are limitations especially when it is necessary to increase both the downlink and uplink data rates.

To improve the area data rate, in addition to the above, the following measures can be considered:

E) Increasing the number of MIMO layers handled by the base station:

Adding more MIMO layers to the base station is key to improving wireless communication capacity. When we can provide extra MIMO layers, it means we can increase the overall area bandwidth. This upgrade helps to send and receive more data faster and efficiently.

F) Improving frequency spatial reuse:

Similar to E, but through spatial multiplexing, the same frequency can be used simultaneously, thereby improving the overall data rate coverage within the area.

From the aforementioned point A, it can be argued that leveraging mmWave is a critical factor in achieving the required data rates in 6G. However, mmWave faces challenges such as short transmission distances and significant degradation due to distance, hindering the use of higher modulation schemes. To implement measure B, antennas need to be placed close to the UE and within a LOS environment. While aspect C largely depends on MNO policies and design, from a technical perspective, mmWave, with its short transmission range and lack of penetrability, can be considered conducive to simpler area design. Measure E, related to C, when considering the entire area, reducing the number of UEs per MIMO layer would decrease the total number of UEs that can be serviced. To prevent this, an increase in the number of MIMO layers is required. However, the use of limited frequencies means simply increasing the number of MIMO layers is not feasible, necessitating strategy F’s spatial multiplexing. Technologies like mMIMO utilizing beamforming are effective for spatial multiplexing. Similarly, creating hotspots with smaller radio coverage for spatial multiplexing is also effective. The short reach and non-penetrative nature of mmWave make it well-suited for these applications.

Another significant gap identified in this study is latency, as shown in Figure 10.

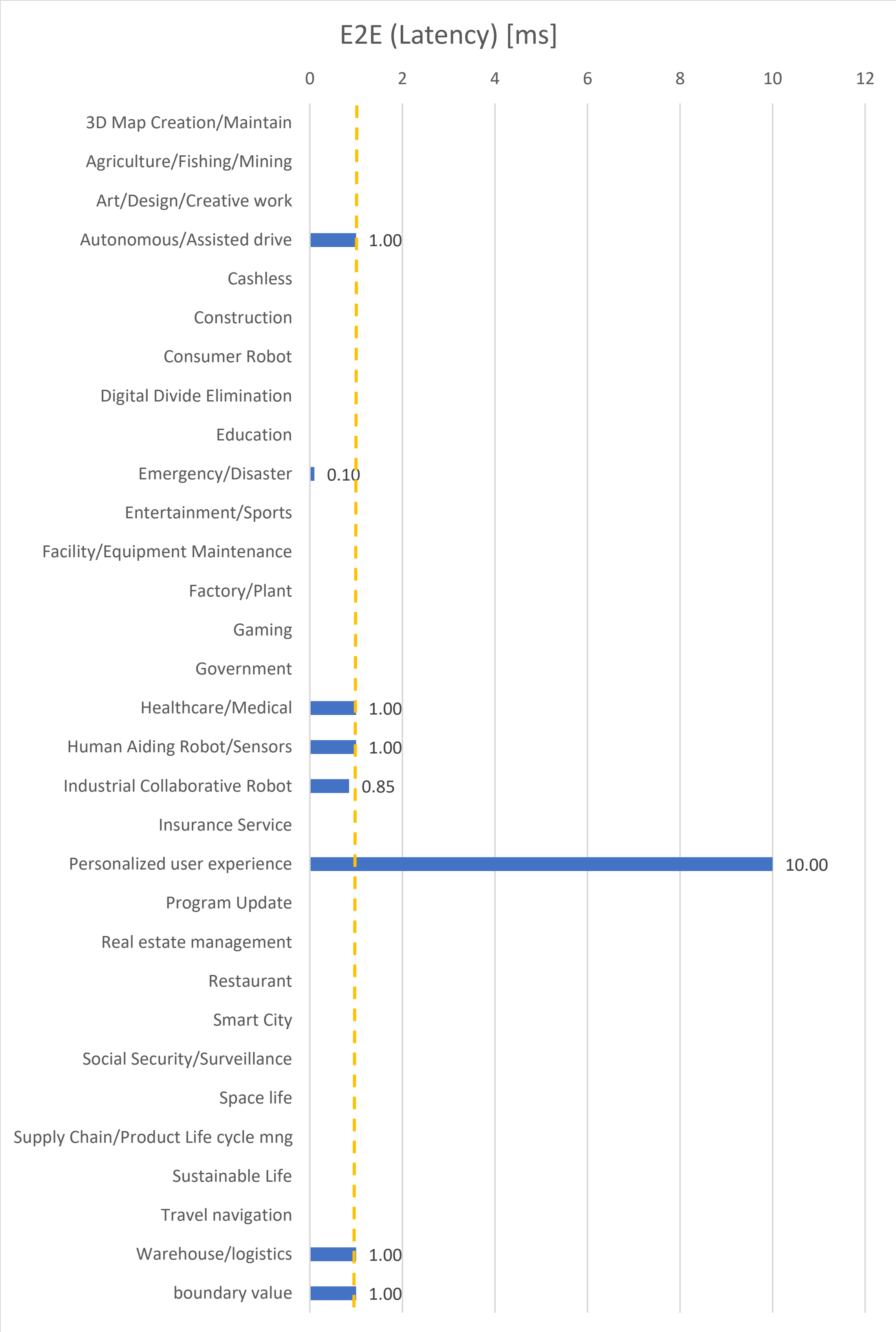


Figure 10 Required maximum E2E latency.

As discussed in Section3.3.3, the E2E transmission delay varies depending on the network configuration, and the data processing requirements specific to each application and device. Therefore, a comprehensive gap analysis for the entire E2E cannot be generalized, and the focus is shifted to the common element, the Wireless Access Network. As can be seen from Figure 9, there are seven use cases where the required E2E communication time is less than 1 ms. This 1 ms boundary value is a target value indicated for 5G capabilities [13], implying that these use cases cannot accommodate additional transmission or processing beyond the Wireless Access Network in a 5G environment. However, considering that the 1 ms indicates average transmission times with retransmissions, it is feasible to achieve transmission times shorter than 1 ms in an optimal Wireless Access Network environment. When considering the use of mmWave, an optimal environment is characterized by a short distance between the UE and the antenna, and additionally, a LOS condition. This is consistent with the conditions required to achieve Option B mentioned above.

As has been discussed, achieving the data rates and latency required by 6G necessitates a combination of the measures A through E.

5.1 Leveraging mWAD to bridge the analyzed gaps

As of today, the most straightforward approach to realize this involves the strategic placement of mmWave-compatible O-RUs in necessary locations. By deploying O-RUs, an increase in the number of MIMO layers can also be expected, which in turn should enhance the overall data rate of the area. However, while beamforming is an effective technology, it faces challenges. For instance, if the UE is mobile or the surrounding environment is dynamic (such as people moving between the UE and the antenna), mmWave signals can be obstructed, leading to unstable communication.

Similar to how mobile robots and drones require seamless handover, there is a demand for continuous signal reception regardless of the location within the activity area. To address such scenarios, the use of D-MIMO, which allows the transmission of the same signal from multiple directions to the UE, is an option. D-MIMO not only allows for the transmission of signals from multiple antennas for the same MIMO layer but also for different MIMO layers. This approach can potentially enhance UDRAT. The mWAD proves to be beneficial in these circumstances.

As applications demanding high data rates become widespread, the number of RUs installed will increase, leading to a corresponding rise in power consumption. Although no use case provided explicit numerical targets, 20 out of 29 SUCs highlighted the importance of energy efficiency. Conversely, while fewer SUCs emphasized cost efficiency, it is self-evident that Mobile MNOs seek cost-effective infrastructure solutions to enhance their facilities. Similar to the DAS technology in the LTE era, mWAD technology transfers RF signals sent from RUs via wires and allows transmission of signals from the same or different MIMO layers through multiple antennas. The antenna terminals can be implemented more simply than O-RUs, with no baseband processing, thus enabling lower power consumption. If RF signals can be transmitted in their analog form, antenna terminals can be made even simpler, eliminating the need for digital processing. Smaller antenna equipment increases installation flexibility and allow for more precise antenna placement.

As of today, in the optical access network domain, 50G-class bidirectional point to point (PtP) access and passive optical network (PON) technologies are standardized by ITU-T. Assuming the current enhanced Common Public Radio Interface (eCPRI) in O-RAN ALLIANCE fronthaul interface, rather mWAD, which requires several times of wireless access network data rate for optical network, at least several hundred Gbps is required. Advanced optical transmission and signal processing technologies, such as the digital coherent technology used in the core network, would be required, potentially degrading power and cost efficiency.

As such, mWAD proves effective for realizing many 6G use cases, but its implementation faces several challenges. The foremost challenge is cable propagation for millimeter waves. High-frequency RF signals like mmWave experience significant attenuation in coaxial cables, limiting antenna extension. Another challenge lies in array antenna control. Most antenna equipment transmitting mmWave utilizes Array Antennas for beamforming, controlling the phase for each antenna element. However, if the RF, processed for transmission once, is transmitted from extended antenna equipment, the RF lacks the necessary signal for phase control, resulting beamforming unfeasible.

To address the mWAD challenges, the utilization of Analog Radio over Fiber (A-RoF) can be considered. A-RoF is a technology that transmits RF signals over optical fiber, enabling low-loss, long-distance transmission even for high-frequency RF like mmWave. Transmitting analog signals eliminates the digital processing in the antenna equipment, contributing to miniaturization. Furthermore, from the perspective of optical transmission, analog signal transmission enables high-frequency utilization efficiency of radio signals through simple analog intensity modulation and direct detection (IMDD) methods, in addition to reducing latency. Moreover, the use of wavelength division multiplexing (WDM) techniques such as Dense Wavelength Division Multiplexing (DWDM) and subcarrier multiplexing (SCM) technologies for transmitting IF signals via frequency multiplexing allows for the overlaying of multiple signals on a single optical fiber, offering significant cost benefits. Regarding beamforming, although it is currently in the research phase, several initiatives are underway [26], and it is expected that a solution will eventually be found.

6 Conclusion

In this study, we analyzed 170 use cases documented in four global documents pertaining to 6G, summarized them into 29 consolidated (summarized) use cases, and identified 31 specific requirements. Furthermore, for each use case, we conducted a detailed gap analysis to specify the requirements, verified the effectiveness of mWAD, and contemplated measures to bridge these gaps.

In 6G, there is an expectation for shared experiences and sensations in environments where the real and virtual spaces merge, such as in the metaverse, interactive live music, immersive sports experiences, remote training, and collaborative creative activities. To realize this, a significant increase in uplink data rates is required, in addition to the continuous expansion of downlink requirements. For instance, the data rates needed for replicating real object in virtual spaces for live sports, live music, or the metaverse demand 14-230 Gbps per object for uplink, while on the viewing side, 48-200 Gbps for downlink is necessary.

Another challenge is the latency. While 5G targeted 1 ms in the Wireless Access Network, applications requiring less than 1 ms of E2E latency have emerged, making the reduction of delay time within the Wireless Access Network a critical issue.

To address these gaps, utilizing mmWave, increasing the number of antennas, and enhancing signal quality by positioning antennas closer to the UE are necessary. These measures align with the features of mWAD, confirming its potential to significantly contribute to the realization of 6G use cases.

However, implementing mWAD poses challenges such as transmitting mmWave signals through the cable with low loss and remotely controlling distributed antenna equipment for beamforming. The use of technologies like A-RoF is effective for the former challenge. A-RoF can also reduce digital processing in antenna devices, contributing to latency reduction. Efforts are underway to transmit Beamforming control signals, and the technical feasibility is becoming apparent. Standardization efforts of these technologies are anticipated for the commercial utilization of mWAD.

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