6GSNS

Smart Networks and Services
Joint Undertaking (SNS JU)
Technical board Working Group

White Paper

6G for Media & Entertainment

Challenges, Opportunities and Future Outlook

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EXECUTIVE SUMMARY

The Media & Entertainment (M&E) sector is undergoing a profound technological and structural transformation. Audiences are shifting towards on-demand, immersive, and interactive content; AI and generative media are becoming integral to production and distribution; and live events increasingly rely on digital augmentation. Against this backdrop, 6G technologies—supported by innovations in AI, edge computing, non-terrestrial networks, sensing, and distributed intelligence—are poised to redefine how media is created, delivered, and experienced.

Within this evolving landscape, the Smart Networks and Services Joint Undertaking (SNS JU) plays a central role in shaping Europe's technological leadership. Through **22 dedicated projects and 46 use cases**, SNS JU is developing and validating the network capabilities, architectural enablers, and experimental platforms that will make 6G-enabled M&E applications technically feasible, economically sustainable, and societally acceptable.

SNS JU projects collectively address the stringent performance needs of next-generation M&E services—ultra-high bandwidth, sub-millisecond latency, massive device density, distributed compute, precise positioning, integrated sensing, and advanced security. Contributions in several critical M&E aspects are highlighted in this paper:

- **Immersive Media and XR** including end-to-end XR architectures, indoor interactive gaming, and multi-camera 360° capture used to validate the delivery of real-time, high-resolution volumetric content to large audiences.
- **Live Broadcasting, Remote Production, and Cloud Media** using Ultra-high-quality video streaming (4K/8K/360°) and real-time multi-screen experiences show how 6G capabilities will enable agile remote production and rich in-venue experiences.
- **Holographic and Volumetric Communications** including delivery of realistic multi-user holographic interactions, combining multi-sensor capture, semantic communication and remote rendering, used to define the backbone for next-generation communications, virtual production, and collaborative industrial design.
- **Sustainability and Energy/Carbon Transparency** measuring and exposing the carbon footprint of media sessions to end users and service providers and as such establishing a foundation for environmental accountability in digital media.
- **Metaverse and Distributed Collaborative Spaces** through the exploration of cross-MNO federated services, trust-by-design architectures, explainable AI, and intent-based interfaces supporting secure, interoperable, and scalable metaverse scenarios across culture, industry, and education.
- **Smart Advertising and User-Centric Applications** via trustworthy, privacy-preserving data use, self-sovereign identity, and dynamic pricing, anticipating new business models aligned with societal values and digital sovereignty goals.

This white paper provides an extensive analysis of the current status of the M&E sector, based on SNS JU experts and an extensive research of the industrial M&E domain, and the promising technologies and features of 6G that stand to bring M&E services to the 2030s. Based on the presented analysis a few key findings may be highlighted:

- **6G is indispensable for next-generation media formats** such as holographic telepresence, real-time volumetric video, and fully immersive XR experiences. These require capabilities beyond 5G, especially in uplink bandwidth, jitter control, synchronized multi-stream delivery, and precise positioning.
- **Edge computing and distributed intelligence are foundational**. Most advanced media applications depend on computation close to the user—reducing latency and enabling complex real-time rendering, AI inference, and sensor fusion.
- **AI becomes pervasive across the entire media chain**, from capture to distribution to user experience personalization. This includes rate adaptation, traffic prediction, security, and automated content creation.
- **Sustainability emerges as a core requirement**. Energy-efficient architectures, carbon-aware service orchestration, and user-visible environmental metrics are essential for future networks and media workflows.
- **Interoperability and standards will determine adoption speed**. Diverse capture technologies, heterogeneous XR devices, and multi-provider network infrastructures require global standards formats, QoS, interfaces, and orchestration frameworks.
- **End-user devices remain a bottleneck**. Despite network progress, device limitations—processing, battery, display, and sensing—currently constrain the quality of immersive applications.

Despite strong progress from SNS JU projects, significant **challenges** remain for large-scale 6G adoption in the M&E sector. Achieving the advanced infrastructure required for sub-THz communications, distributed MIMO, and edge-centric architectures demands high investment, while uplink limitations still constrain volumetric capture and remote production. Immersive and metaverse applications also heighten privacy and security risks due to their dependence on sensitive biometric and behavioural data. Interoperability gaps between devices, platforms, and formats threaten ecosystem fragmentation, and today's end-user devices—limited in battery, processing, display, and cost—continue to restrict the quality of immersive experiences.

At the same time, 6G offers major **opportunities** to transform M&E through hybrid digital-physical events, immersive broadcasting, holographic telepresence, and cloud-native collaborative production. Ultra-high bandwidth, low latency, and distributed AI will support richer, more interactive content and personalized user experiences, while metaverse applications expand into culture, education, tourism, and industry. Sustainability will become a central value driver as carbon-aware streaming and energy-efficient delivery influence both operators and consumers. Early 6G adoption is expected in premium immersive services and professional production environments, broadening as devices mature and standards solidify. With continued investment, coordinated regulation, and leadership in R&I, Europe is well positioned to shape the global future of 6G-enabled media.

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ABBREVIATIONS

Abbreviation	Definition
3CN	3C Network – Connected, Collaborative Computing
3GPP	Third Generation Partnership Project
6GF	6G Forum
6G-IA	6G Industry Association
AI	Artificial Intelligence
AIOTI	Alliance for IoT and Edge Computing Innovation
AR	Augmented Reality
ATIS	Alliance for Telecommunications Industry Solutions
B5PC	Beyond 5G Promotion Consortium
B6GA	Bharat 6G Alliance
CCSA	China Communications Standards Association
CDN	Content Delivery Network
CHIPS-JU	Chips Join Undertaking
CO2e	CO2 emissions
CPD	Central Processing Data center
CSA	Coordination and Support Action
CSO	Civil Society Organization
DG-CNECT	Direction General CNECT
EC	European Commission
ECCC	European Cybersecurity Competence Centre
ECS	Edge Computing System
ECSO	European Cyber Security Organisation
eMBB	enhanced Mobile Broadband
ESA	European Space Agency
ETP	European Technology Platform
ETSI	European Telecommunication Standards Institute
FL	Federated Learning

FSTP	Financial Support to Third Party
HE	Horizon Europe
HPC	High Performance Computing
ICT	Information and Communication Technology
IMT-2030	International Mobile Communication 2030 (6G)
IPCEI	Important Projects of Common European Interest
ISAC	Integrated Sensing and Communications
ITU-R	International Telecommunication Union – Radiocommunication Sector
KPI	Key Performance Indicator
KSO	Key Strategic Orientation
KVI	Key Value Indicator
LIME	Local Interpretable Model-agnostic Explanations
M&E	Media&Entertainment
MEC	Multi-access Edge Computing
MIMO	Multiple Input – Multiple Output
ML	Machine Learning
mMTC	Massive Machine Type Communication
MNO	Mobile Network Operator
MR	Mixed Reality
NESSI	Networked European Software and Services Initiative
NGA	Next G Alliance
NGMN	Next Generation Mobile Networks Alliance
NGO	Non-Governmental Organization
NPN	Non-Public Network
NTN	Non-Terrestrial Network
NWE	NetworldEurope
PAG	Policies and Data Governance (PAG)
PQC	Post-Quantum Cryptography
PSCE	Public Safety Communications Europe
QKD	Quantum Key Distribution
QoE	Quality of Experience

QUIC	Quick UDP Internet Connections
R&I	Research and Innovation
RAN	Radio Access Network
RIC	RAN Intelligent Controller
RIS	Reconfigurable Intelligent Surface
RT	Real Time
SB	Steering Board
SHAP	SHapley Additive exPlanations
SME	Small or Medium sized Enterprise
SNO	Satellite Network Operator
SNS JU	Smart Network and Services Joint Undertaking
SoC	System on a Chip
SRIA	Strategic Research and Innovation Agenda
TB	Technology Board
TF	Task Force
TN	Terrestrial Network
TRL	Technology Readiness Level
TSDSI	Telecommunications Standards Development Society
UAV	Unmanned Aerial Vehicle
UGC	User generated content
URLLC	Ultra-Reliable Low Latency Communication
VR	Virtual Reality
VSC WG	Visual Studio Code Working Group
XAI	eXplainable AI
XR	Extended Reality

1. INTRODUCTION

Media and Entertainment (M&E) is a very wide sector which covers a number of services such as Books, TV, Cinema, Film production, Advertising, Radio, Gaming, Gambling, Music, social media, and more, that are using communication channels since a long time. The main commonality between these sub-sectors is that they all need high bandwidth and low latency. However, a number of new network functions could also bring new opportunities to develop innovative use cases.

The Smart Networks & Service Joint Undertaking (SNS JU) is a public-private partnership operating autonomously under the Horizon Europe Programme, responsible for funding research and innovation activities in Europe regarding telecommunications networks and services. More than 60 projects are already operational under the umbrella of the SNS JU[1], researching, developing, testing and validating technological solutions for the advancement and development of 6G networks. Several of these projects are developing and experimented M&E use cases, technical solutions and applications, as part of their efforts to deliver the stringent Key Performance Indicators (KPIs) set forth for 6G and to generate innovative M&E services.

This white paper is produced by the SNS JU Technology Board (TB), which is the main collaborative body of SNS JU technical experts, and aims to introduce the work taking place within the SNS JU projects, relevant to M&E. The contributions of the 22 SNS JU projects to the M&E sector is described in the following sections as well as the keys findings, the key challenges and the future outlooks. They are illustrated through the 46 use cases developed and experimented by projects.

This first section will give some key insights with regards to 6G technologies that could benefit the M&E sector.

1.1. 6G TECHNOLOGY BACKGROUND

6G (sixth-generation) technology represents the next major leap in mobile communications, building upon the advancements of 5G. It aims to offer ultra-reliable, low-latency, and high-throughput connectivity, enabling a wide range of innovative applications and services.

[1] https://smart-networks.europa.eu/

Key Features and Capabilities

- **Ultra-High Data Rates**: 6G is expected to achieve peak data rates of up to 1 Tb/s, significantly surpassing the capabilities of 5G.
- **Low Latency**: The technology aims to reduce latency to as low as 0.1ms, enabling real-time applications such as autonomous driving and remote surgery.
- **Massive Connectivity**: 6G networks are designed to support up to 10^8 devices per square kilometer, facilitating the Internet of Things (IoT) and smart cities.
- **Energy Efficiency**: Enhanced energy efficiency is a critical goal, with 6G networks aiming to reduce power consumption while improving performance.
- **Security and Privacy**: 6G incorporates advanced security measures to protect user data and ensure privacy, addressing the growing concerns in the digital age.

Foundational Technologies

- **Terahertz (THz) Communication**: Utilizing frequencies in the terahertz range (including sub-terahertz) to achieve ultra-high data rates and support new applications.
- **Ultra-Massive MIMO**: Deploying a large number of antennas to improve spectral efficiency and coverage.
- **Machine Learning (ML) and Deep Learning (DL)**: Optimizing network slicing and addressing security challenges within 6G networks.
- **Network Slicing**: Creating flexible, service-specific logical network partitions to meet diverse requirements.
- **Reconfigurable Intelligent Surfaces (RIS)**: Enhancing signal propagation and coverage by dynamically adjusting the reflective properties of surfaces.

Applications and Use Cases

- **Extended Reality (XR)**: Enabling immersive virtual and augmented reality experiences.
- **Smart Cities**: Supporting smart infrastructure and services for urban environments.
- **Autonomous Systems**: Facilitating the operation of autonomous vehicles and drones.
- **Healthcare**: Enabling remote medical consultations and advanced diagnostic tools.
- **Industrial IoT**: Enhancing manufacturing processes and supply chain management.

Challenges and Considerations

- **Technical Challenges**: Including the integration of the aforementioned foundational technologies, the propagation of terahertz waves, dynamic network integration, and ensuring network security.

- **Non-Technical Considerations**: Addressing regulatory, societal, and market dynamics to ensure the successful implementation of 6G.

6G technology is poised to revolutionize the way we communicate and interact with the digital world, offering unprecedented capabilities and opportunities for innovation.

1.2. IMPORTANCE OF THE 6G IN M&E

The future 6G ecosystem, as described in IMT-2030 [1], aims to extend and enhance the current IMT-2020 scenarios (eMBB, URLLC, mMTC) to Immersive communications, Hyper Reliable & Low-Latency Communications and Massive Communications. Additionally, it aims to create new ones by combining them together. This clearly states that 6G is focusing on verticals and use cases that demand stringent requirements and advanced features such as the media industry. Following, we highlight several 6G-related expectations and topics that will contribute to the development of advanced and innovative use cases in the M&E sector.

Simplicity & Maintainability: Simplified network management such as with automated configuration tools (e.g., Quality on Demand via network APIs) will increase accessibility to advanced connectivity solutions for various industries, particularly in automotive use cases like teleoperated driving and high-bandwidth video streaming. Delays in standardisation and global interoperability pose challenges.

- **Global Coverage**: Connectivity in underserved and remote areas for critical applications like telemedicine and smart agriculture. Despite immature low-energy networking technologies and high infrastructure costs, satellite connectivity can provide ubiquitous coverage in areas previously unreachable by terrestrial networks.
- **Ultra Low Latency**: Real-time capabilities are crucial for applications like remote surgery, autonomous vehicles, human communication, and industrial automation. Economic barriers, such as high development costs and limited edge device suppliers, present challenges.
- **AI-Powered Services**: Intelligent automation, cognitive radio, and predictive analytics integrated into network operations can revolutionise public safety and emergency response. Challenges include energy consumption, infrastructure complexity, requiring a high number of base stations, and operational hurdles in managing large-scale deployments. Network APIs, offering customisable and scalable functionalities, can address these challenges effectively.
- **Ultra-High Bandwidth**: Support for data-intensive applications and dense device networks. Limited network availability and spectrum allocation issues currently hinder such advancements. Integrated sensing and communication technologies offer game-changing potential by enabling real-time data acquisition necessary for these applications.

- **Security and Resilience**: Enhanced security and resilience for use cases in which ultra-reliable communication is vital. These applications face challenges due to their reliance on complementary technologies such as satellite communication. Cloud-native networks offer seamless scalability and flexibility, ensuring robust and secure operations in enterprise and critical sectors.
- **Economic Sustainability**: Reduced deployment and operational costs are necessary to make connectivity solutions viable for SMEs and emerging markets. Solutions, are currently hindered by limited funding for early-stage technologies. Low-energy communications provide a sustainable and cost-effective approach, supporting energy-efficient IoT devices and broader adoption in developing regions.

Comparing 5G and 6G, it is obvious that some elements will provide better solutions for Media & Entertainment use cases and services such as Environment rendering, high definition 4K, 8K, 16K,), augmented experience (2D, 3D, stereoscopic), Precise positioning/timing, Environment understanding or Environment control, AI for transmission optimization, among others. The goal of the 6G ecosystem regarding Media & Entertainment should be to fill the gaps that 5G could not, offering tailor-made solutions for the industry.

1.3. OBJECTIVE OF THE WHITE PAPER

This white paper, produced by the SNS JU Technology board members and the corresponding projects that are addressing M&E, has the objective to provide an overview of what SNS JU projects have done and highlight the results that will benefit to the M&E sector.

It has also the objective to identify remaining weaknesses that should be taken into consideration by future projects for the 2027 WP and the next FP10.

46 use cases developed by 22 SNS JU projects are addressing different aspects of the M&E sector. This huge R&I activity has brought a lot of results that could benefit the M&E sector stakeholders.

In 2025, experiential entertainment moves into the spotlight, AI goes mainstream, streaming profitability accelerates and M&E executives recalibrate portfolios as linear fades.

- Investments continue in location-based entertainment as consumers demand access to experiences.
- The use of artificial intelligence (AI) and generative AI (GenAI) will gain momentum, but M&E executives want to see the ROI.
- All eyes are on direct-to-consumer (DTC) models for sustainable profitability.
- Linear TV has arrived at a strategic crossroads: harvest or divest.

5G offers a range of key technologies to enable and support these cases. The main ones are higher bandwidth, both downlink (mainly) but also uplink; edge computing that enables latency reduction in some uses; support for increased user density – to reduce congestion both for production and consumption; slicing and orchestrated virtualised services using 5G Core to enable QoS "guarantees" for paying customers in stand-alone (SA) networks; NPN networks and NPN-PN roaming and collaboration models; and broadcast/multicast support.

Looking to foreseen network development, AI, Multi-access Edge Computing (MEC) and NTN should find a place in the M&E technical chain but from the end user point of view, the Network is not the main weakness today, end devices have also a big role in the end-to-end user experience.

In this White Paper, we are developing the following aspects:

- What are the key requirements from the M&E sector?
- What technologies are being investigated?
- What is the added value of B5G/6G for these use cases?
- What are the main challenges and envisioned solutions?
- What has been achieved so far within SNS JU?
- What are the lessons learned and way forward?
- What are the Business models?

2. UNDERSTANDING 6G TECHNOLOGY

This section is providing high level information regarding the next 6G networking technology with regards to the vertical sectors. A number of new functionalities introduced in the 6G network could benefit to the vertical sector.

2.1. DEFINITION AND OVERVIEW OF 6G

2.1.1. WHAT IS 6G?

6G (sixth-generation wireless) is the successor to 5G cellular technology. 6G networks will be able to use new frequency spectrums than 5G networks and provide substantially higher capacity, higher reliability and much lower latency.

As 5G continues to establish itself as a backbone of modern communications with enhanced bandwidth, reduced latency, and massive IoT integration, 6G has already emerged with the promise of revolutionizing the network ecosystem even further. 6G is expected not only to integrate advanced technologies, such as terahertz (THz) frequency band communications, but also the most comprehensive artificial intelligence (AI) capabilities, and sophisticated network slicing for services at unprecedented data rates in the order of terabits per second and near-zero latency. 6G is envisioned to enable pervasive and ubiquitous connectivity, further extend the network and compute continuum, and combine public networks and non-public networks (NPN) to provide connectivity to underserved areas, aiming to extending network coverage and boost the performance end-to-end.

Considering the scale and rapid nature of this network evolution, it has become both technologically and conceptually rather challenging to safeguard security and privacy of the system and its users, such as when protecting sensitive user or critical data, securing ultra-low latency communication, detecting novel cyber threats, and ensuring the integrity of the network infrastructure. Indeed, massive connectivity intrinsic to 6G networks and distributed operation along a huge number of highly heterogeneous infrastructure in a multi-provider/infrastructure/stakeholder/services environment, increases with no doubt the attack surface to non-yet envisioned limits, and urgently demands for innovative approaches to secure a multitude of interconnected devices and applications. In addition, the integration of artificial intelligence (AI) and the related machine learning (ML) algorithms in 6G networks introduces concerns related to the privacy of user data and the potential biases and misuse of AI algorithms. The entanglement of devices and technologies in a cloud continuum which ranges from the hyperscale cloud platforms to the very far edge requires full coordination, increasing the complexity of the management of networks, while introducing new and heightened security challenges. The broad scope of 6G network that integrates aerial and satellite networks (Non-Terrestrial Networks, NTN), Non-Public Networks (NPN) and Public Network Integrated NPNs (PNI-NPN) furthermore amplify security and privacy challenges. Consequently, guaranteeing reliable 6G services operation becomes a must to guarantee a wide adoption of the 6G technology.

The 6G technology market is expected to facilitate large improvements in the areas of imaging, presence technology and location awareness. Working in conjunction with artificial intelligence (AI), and leveraging the cloud-continuum paradigm, 6G may substantially contribute to guarantee fast and reliable connectivity to the different available infrastructures within the continuum, from the edge up to the cloud. In this context a dedicated AI-assisted process may be responsible for identifying the best infrastructure to each process (i.e., service, task, job), including decisions about storage, processing and sharing, thus maximizing resources utilization while also optimizing service execution. Moreover, the large and stable connectivity offered by 6G will facilitate distributed processing functionalities, extremely useful to preserve data privacy in M&E sensitive applications, for example using Federated Learning (FL) to train models at local premises with no need to disclose sensitive data.

Defining use cases is an important step in the development of any new mobile network technology. Use cases describe the kind of functionality that needs to be provided. Use cases are also used to derive new functional requirements and a sound justification for the targeted performance requirements.

One of the key use case family taken into consideration in the development of the 6G technologies is the Virtual world and Immersive technologies which is also widely used by the M&E sector. This use case family is based on XR technologies.

The immersion is built through the combination of immersive and sensorial technologies (e.g., 3D visual perception, spatial audio, haptics) and the synchronisation of data streams so that multiple participants have simultaneous, consistent, and collaborative experiences.

To achieve this superior Quality of Experience (QoE) and seamless service continuity, data rates are required beyond what 5G typically delivers, plus strict E2E latency and reliability guarantees.

Additionally, new 6G capabilities such as sensing, positioning, and AI/ML are key technology enablers for Intelligent and Resilient System.

2.1.2. EVOLUTION FROM 5G TO 6G

The level of 6G capacity and latency will extend the performance of 5G applications. It will also expand the scope of capabilities to support new and innovative applications in wireless connectivity, cognition, sensing and imaging. Table *1* a comparison between the 5G and the 6G (expected) Key Performance Indicators (KPI).

Table 1: 5G/6G comparison

Capabilities	IMT-2030 (6G)	IMT-2020 (5G)
Peak data rate	50-100-200 Gbps	20 Gbps
User experience data rate	300-500 Mbps	100 Mbps
Spectral efficiency	1.5 – 3 x IMT2020	-
Area Traffic Capacity	30 – 50 Mbps/m2	10 Mbps/m2
Connection Density	106-108 dev/km2	106 dev/km2
Mobility	500-100 kmph	500 kmph
Latency	0.1 – 1 ms	1 ms
Reliability	10-5-10-7	10-5
Area Traffic Capacity	30 – 50 Mbps/m2	10 Mbps/m2

2.2. KEY FEATURES OF 6G

6G offers a number of new functionalities which are sometimes an extension of the existing 5G. They are providing new possibilities.

<u>Key 6G features for M&E use cases</u>

- **Immersive Communication:** Immersive communication (IC) will be one of the key service classes of the 6G wireless networks. It will introduce interactive services, such as extended reality (XR), holographic communication, cloud gaming, high-definition video (4K and 8K) streaming, and immersive event experiences over cellular networks. These services demand a large volume of data and require immersive throughput values. For instance, a live VR concert, streaming to thousands of participants simultaneously, requires a wireless network capable of handling substantial data rates without compromising the user's QoE. According to the ITU IMT-2030 vision [29], the envisioned throughput for IC peaks at 1 Tbps, with the user-experienced data rate of at least 300 Mbps, which far exceeds the capabilities of IMT-2020.

- **Hyper Reliable and Low Latency Communication (HRLLC):** HRLLC is the extension of 5G's URLLC to enable new services where the latency from one or more connected devices are the utmost important. The relevant services are interactive gaming, industrial automation, and autonomous vehicle.
- **Advanced connectivity and network slicing:** Network slicing is a way of creating multiple unique logical and virtualized networks on top of a shared infrastructure using software-defined networking (SDN) Integration with AI and IoT.
- **Convergence with NTN:** 5G NTN refers to the integration of satellite communication and aerial platforms into the 5G ecosystem. Such combination provides extended and global coverage especially in remote, underserved or disaster affected regions.
- **Multi-access Edge computing:** MEC moves computing power closer to the end-user in order to enable applications and services requiring unique connectivity characteristics such as ultra-low latency.
- **Edge AI and AI CDN:** Integrating AI into content delivery network (CDN) strategies enhances web performance, security, and website personalization. AI-powered CDNs optimize real-time content delivery, predict and adapt to traffic patterns, and offer personalized experiences to users, significantly improving engagement and satisfaction
- **Environment rendering/understanding/control:** 6G expands into ubiquitous environments and pursues higher capacity, numerous sensing and artificial intelligence (AI)-based methods have emerged to combat random channel fading. 6G will propose an environment intelligence communication (EIC) based on wireless environmental information theory (WEIT).
- **Ultra High definition, 2D, 3D, 4K, 8K, 16K:** 6G will enable the delivery of ultra-high definition (4K, 8K, 16K) and 3D content thanks to its high data rates and ultra-low latency, providing an immersive experience for entertainment, education and communication.
- **Precise positioning/timing:** While positioning in 5G requires the active participation of a 5G-enabled device, passive sensing of the environment will be one of the disruptive features in 6G. For the envisioned use cases, 6G will also need to enhance the localization accuracy to below one centimetre.

  High accuracy positioning and timing in the order of sub-cm and nano-second level. This may be required for applications like positioning and industrial automation.

- **Support highly distributed processing along the continuum:** 6G Computing Continuum is an end-to-end compute and software platform for realizing large intelligent surfaces and its tenant users and applications.
- **Integrated Sensing and Communications (ISAC):** Sensing operation of passive object(s) that is integrated to the cellular communication network is targeted to enable new services, including object detection/tracking and gesture recognition for interactive gaming, and intelligent augmented reality (AR) navigation. Environment understanding and environment control can be fulfilled by ISAC operation.

3. THE IMPACT OF 6G ON MEDIA AND ENTERTAINMENT

3.1. ENHANCED USER EXPERIENCE

The M&E industry is undergoing a profound transformation driven by rapid technological advancements. From the rise of immersive experiences powered by augmented reality (AR), virtual reality (VR) and new devices to the demand for high-quality streaming and real-time interactions, audiences are engaging with content in more dynamic and personalised ways than ever before. At the forefront of this evolution is artificial intelligence, enabling everything from automated content creation to audience analytics and personalized recommendations.

The emergence of 6G promises to profoundly impact the media and entertainment sector, building on the advancements of 5G. Many existing or new mobile applications will benefit from the 6G wireless networks. This will be possible thanks to 6G's much higher data bitrates (up to 1 Tbps), ultra-low latency (sub-millisecond), more intelligent connectivity through AI and edge computing, device density of up to 10 million devices per km^2, jitter control less than 1ms, location accuracy with less of 10cm precision and much higher energy efficiency.

While 5G has already transformed how media and entertainment content is produced, distributed, and consumed, 6G will, in fact, represent a fundamental leap in the quality, inclusiveness, and immersive-ness of user experiences. The focus will not solely be on technological breakthroughs, but on how these advances enable seamless, personalized, and emotionally engaging interactions between users and digital media environments. With higher data rates, users will access ultra-high-resolution and volumetric content instantaneously, removing buffering or compression artifacts that currently limit immersion. Lower latency and enhanced reliability will enable truly synchronized multi-sensory experiences—critical for live entertainment, collaborative creativity, and interactive storytelling. The scalability and energy efficiency of 6G will support massive numbers of concurrent users in virtual and hybrid spaces without compromising quality, ensuring that premium experiences are accessible globally and sustainably. Furthermore, interoperability with low-end and legacy devices will promote inclusivity, extending advanced M&E experiences to users regardless of their device capabilities or connectivity context.

Beyond the technical enablers, 6G will also introduce new societal, economic, and environmental key values as identified by the 6G-IA white papers on 6G societal drivers. These include human-centric connectivity, digital inclusion, sustainability, and value creation across creative ecosystems. In the M&E domain, this means enabling fairer creative economies, supporting new forms of artistic expression, and facilitating cross-cultural participation in immersive environments. Ultimately, 6G will redefine the media and entertainment experience as not only faster or more immersive—but more human, inclusive, and sustainable.

Many of the current 6G SNS projects, especially those in Streams B and C, offer an overview of the enablers that could support the needs of the M&E sector in the coming years with a view to enhancing user experience and reinforcing EU competitiveness. These projects collectively aim to create the technological foundation for 6G that meets the evolving demands of M&E, while also addressing sustainability, accessibility and immersive experience requirements.

The R&D areas, most relevant to the M&E sector, being addressed by the program include the following *(6G SNS project names in brackets*):

- Virtualised network elements for Radio Access Network (RAN) management *(NANCY[46])* and densification of radio access points to enable multi-stream transmission *(SEASON[50])*.
- Integration of terrestrial and non-terrestrial networks to enhance connectivity especially in underserved areas *(5G-Stardust[49], 6G-NTN[44])*.
- Short-range wireless communication and subnetworks to improve latency, reliability, and interference management *(6G-Shine[35])*.
- Novel architectures based on AI and/or computing paradigms to enhance performance, provide security, improve energy efficiency and anticipate user needs *(Adroit6G[37], 6G-Intense[51], Horse-6G[43], MARE[52], Sunrise-6G[41], Flecon-6G[53])*.
- New platforms, cell-free networks and Reconfigurable Intelligent Surfaces (RIS) to support seamless immersive reality experiences *(Hexa-X II[39], 6G-Bricks[34])* or to integrate of AI, AR/VR/XR, metaverse and gaming technologies supporting edutainment in cities and museums *(TrialsNet[55])*.
- New testing infrastructures to validate future B5G / 6G use cases *(6G XR[36], 6G Sandbox[42], Imagine B5G[33], Fidal[48])*.
- New protocols and methods to reduce energy consumption, including using the Thz wave spectrum *(EXIGENCE[45], Teragreen[38])*.

- Development of the world's first 6G transmitter and receiver microchip technology *(FirstTo6G[54])*.

The most promising M&E areas that will largely benefit from B5G / 6G, some of which are already addressed by current projects, are listed below.

- Immersive Media (AR/VR/XR and metaverse). 6G will enable real-time, high-resolution streaming of immersive experiences without motion lag or latency, for full-sensory VR concerts, sports, and events, holographic communication and entertainment.
- Cloud Gaming and eSports. Games streamed over the cloud with no console/PC required, smoother and more interactive multiplayer gaming (metaverse). Enhanced spectator experiences with immersive viewing modes.
- Live Broadcasting and Remote Production. 6G allows for high-resolution video (e.g., 8K or holographic) to be streamed and processed in real time, from virtually anywhere.
- Content Creation. Virtual production creators can leverage edge computing and AI to produce content collaboratively in real time, using cloud-based tools and virtual environments. AI-assisted editing and synthetic media generation.
- Social media. Faster and richer content sharing with immersive or interactive features enabling new monetization and engagement models.
- Smart Theme Parks and Location-Based Entertainment. On-site connectivity supports interactive and AI-driven attractions with ultra-low latency responsiveness.
- Advertising and Personalized Content Delivery Ultra-fast, AI-driven targeting and dynamic rendering of personalized ads in real time including real-time consumer sentiment analysis via connected sensor.

3.2. CONTENT CREATION AND DISTRIBUTION

This white paper delves into innovative solutions for content creation, highlighting several key advancements. One of the notable developments is volumetric capturing, which allows for the creation of highly immersive and interactive content. This technology captures a three-dimensional space, enabling viewers to experience content from multiple angles and perspectives. This is particularly beneficial for applications such as virtual reality (VR) and augmented reality (AR), where a more immersive experience is desired.

In addition to volumetric capturing, this white paper also discusses real-time multi-screen information. This technology enables content to be displayed simultaneously across multiple screens, providing a seamless and synchronized viewing experience. This is especially useful in environments such as sports bars, control rooms, and other settings where multiple displays are used to present information.

Another significant advancement mentioned is immersive capturing. This technology enhances the viewer's experience by creating content that is more engaging and realistic. It is particularly useful for applications such as immersive news broadcasting, where viewers can feel as if they are part of the scene being reported.

The document also explores new advertising possibilities enabled by these advancements in content creation. With the ability to create more immersive and interactive content, advertisers can engage their audience in new and innovative ways. This could include interactive ads that allow viewers to explore products in a virtual environment or ads that are tailored to the viewer's preferences and interests.

On the distribution side, the document highlights improvements in low latency. Low latency is crucial for applications that require real-time interaction, such as live streaming, online gaming, and remote control of machinery. By reducing the delay between the transmission and reception of data, these applications can operate more smoothly and efficiently.

Furthermore, the document discusses various new use cases and applications enabled by 6G and other emerging technologies. One example is multi-screen information on mobile smartphones, which enables users to access and interact with content across multiple devices seamlessly. Additionally, the document mentions immersive viewing experiences at home via VR headsets, providing users with a more engaging and realistic way to consume content.

Overall, the advancements in content creation and distribution discussed in the document have the potential to revolutionize the way we create, distribute, and consume content. These technologies enable more immersive, interactive, and engaging experiences, opening up new possibilities for various applications and industries.

3.3. M&E SERVICES AND APPLICATIONS

New M&E services and application are enabled by 6G and other emerging technologies:

1. Applications like ***immersive news broadcasting*** [2] with volumetric capture require significant bandwidth while XR headsets have limited capabilities, calling for remote-rendering architectures,
2. Users receive ***multi-screen information*** on mobile smartphones, allowing them to select different TV feeds in real-time, while being at the venue the game is played,
3. Users access the ***sports match*** at home via ***VR headsets***, with cameras positioned court-side providing a seamless immersive viewing experience,

4. Users get full '***Carbon footprint transparency'***, the inclusion of metrics such as "Instant Carbon Footprint" or "Total Daily CO2" explicitly during video streaming services (incl. live events), on Over the Top (OTT) platforms, or video conferencing. New features in 6G will enable this,
5. ***Networked Music Performance (NMP)*** is the name given to music played live, between remote musicians, through audio over IP technologies,
6. ***Advertisers*** of products and services find their customers on shared apps where citizens expose their wants and needs in a very generic or very specific way,
7. ***Real-time holographic communications***, via 3D holographic representations of users captured in real time, bring the promise to become a dominant social interaction, collaboration, and communication medium in the near future,
8. The ***Metaverse*** relies on high-quality, multimodal data sources exchanged in real time across distributed entities to deliver rich, interactive, and immersive experiences. It represents a paradigm shift in how humans interact with digital content, the environment, and each other. Several collaborative scenarios will come to live using 6G.

4. USE CASES AND APPLICATIONS

This section provides an outlook of the use cases developed by some SNS JU projects that are targeting M&E applications. For each use case, a short description of the role of 6G is also provided. Table *2* provides an overview of the addressed use cases per project while more detailed use case descriptions are available in Appendix A.

Table 2: Overview of the SNS projects targeting M&E use-cases.

Project	Corresponding Media & Entertainment use case
SEASON [50]	Next-Generation AR/XR Experiences with Smart Optical Networks
6G-SHINE [35]	Indoor interactive gaming
TrialsNet [55]	Sport fan engagement through immersive technologies
EXIGENCE [45]	Media streaming carbon footprint transparency
FIDAL [48]	Networked Music Performance
6G4Society [31]	Smart Advertising
6G-XR [36]	Holographic communications
6G-BRICKS [34]	Holographic communications
SAFE-6G [47]	Trustworthiness for collaborative metaverse scenarios
IMAGINE-B5G [33]	Dynamic XR, Enhanced Touristic Experiences, Bidirectional Education with holographic cabins, etc.
UNITY-6G [32]	Holographic communications
HORSE-6G [43]	Holographic communications

4.1. VIRTUAL AND AUGMENTED REALITY

Extended Reality (XR), which encompasses the whole set of immersive technologies such as Augmented Reality (AR) and Virtual Reality (VR), offers many use-cases which could benefit from 6G. XR requires high QoS from the network since many remote users may need to collaborate in real time. Applications like immersive news broadcasting [2] with volumetric capture require significant bandwidth while XR headsets have limited capabilities, calling for remote-rendering architectures. Interactive experiences such as VR gaming require ultra-low latency while cultural events retransmitted live in XR [3] can target large audiences.

To meet the stringent requirements of XR applications, the SEASON project [50] introduces a new architecture for self-managed, high-capacity, and energy-aware optical networks. By combining real-time telemetry, automated orchestration, and spatial fiber multiplexing, SEASON project[50] sets a blueprint for how networks can adapt to the demands of future immersive media—scaling performance without scaling energy consumption. SEASON project [50] already deployed a full end-to-end architecture delivering AR/VR content to users equipped with head-mounted displays. Key components included a Multicore Passive Optical Network (PON), Software-Defined Orchestration and Edge Computing for XR. A more detailed explanation of the project use-cases and outcomes is available in Annex A.3.

The 6G-SHINE project [35] also targets scenarios with extreme requirements in terms of latency, reliability, or data rates. The project aims at providing disruptive cost-effective solutions to deal with major challenges such as signal blockage, interference due to densification, and proneness to malicious attacks. One of the use-case of the project revolves around providing high quality experiences for indoor XR gaming. To do so, the edge server could provide input to the device attached to the users (i.e., actuators) so that the game player experiences sensation of the game in a form of, for example, vibration, heating. This sensation inputs shall be synchronized with the XR scene delivered to the game player. Furthermore, the XR experiences (e.g., XR scene, sensation) shall also be synchronized among all the game players. More details about the 6G-SHINE project [35] is given in Annex A.4.

4.2. LIVE STREAMING AND BROADCASTING

Building on the capabilities of 5G, 6G technology marks a transformative leap for live streaming and broadcasting, promising to redefine how media content is produced, delivered, and experienced, thus enabling a new generation of immersive, interactive, and sustainable media services.

With 6G, live events—such as sports, concerts, and cultural performances—can be broadcast in ultra-high definition, 360° video, and even holographic formats, reaching audiences both in-venue and remotely with unprecedented realism. The integration of edge computing and AI allows for real-time content adaptation, low-latency interactions, and dynamic resource allocation, ensuring a seamless experience even in high-density environments like stadiums. Moreover, 6G's network slicing and beamforming capabilities enable dedicated, high-throughput connections for both professional broadcasters and end-users, supporting scalable and resilient service delivery. The 4 use cases below, from the FIDAL [48], TrialsNet[55] and EXIGENCE[45] projects, showcase the impact in sports media services, immersive fan engagement and networked music performance, and carbon footprint transparency in media streaming applications as part of sustainable ICT.

4.2.1. ADVANCED SPORTS AREA MEDIA SERVICES

The emergence of 6G technology will open new possibilities for innovative and engaging experiences in large sports events. With the increasing demand for real-time updates and immersive content, new rich media content service applications will become possible, targeting the enhancement of the end-user in-stadium experience, by allowing fans to access a wide range of multimedia content while also serving as the content provider in some cases.

This will allow high-quality video feeds from different angles, including features UHD and 360 degrees video, as well as the use of Augmented Reality experiences, all in real-time in terms of end user perception. This poses important challenges in terms of bandwidth management and scalability of resources as the number of end users increases. Video feed processing for quality and content homogeneity purposes, and especially low end-user perceived latency are also key characteristics that should be met especially for large scale service deployments.

Two related scenarios are explored in the FIDAL project[48]: Enriched high quality video content collection and distribution; and Event media content extensions including end-user generated video material. The first one considers first the upload of sport event media contents (e.g., UHD 8k and 360° VR) from several professionals or semi-professionals. The second one targets (professional) end-user generated video contents to be pushed through the video content management service (i.e., the FIDAL StreamSelector Network Application). Registered end-users have the capability to push video streams with standard quality through the video stream pusher application on their end-devices or the User Generated Content (UGC) capturing application on their smartphone. More details are provided in Annex A.1.

4.2.2. IMMERSIVE FAN ENGAGEMENT

The TrialsNet [55]UC10: Immersive Fan Engagement, successfully delivered a virtual reality live broadcast of a basketball game leveraging YBVR´s (https://ybvr.com/) immersive streaming technology, deploying 180° and 360° cameras strategically positioned around the basketball court. These cameras were connected to the production system and seamlessly transmitted immersive live video feed over B5G stand-alone network installed within the stadium.

The use case featured two distinct scenarios:

- **In-Venue experience**: Users receive multi-screen information on mobile smartphones, allowing them to select different TV feeds in real-time. This scenario requires low latency, precise geolocation, and optimized downlink to serve video feeds to numerous smartphones within the venue.
- **At-Home experience**: Users access the sports match via VR headsets, with cameras positioned court-side providing a seamless immersive viewing experience.

The final match took place on 16th of March 2025 during a basketball match of Movistar Estudiantes vs Súper Agropal Palencia at Movistar Arena, Madrid. Figure 1 illustrates the deployment of four 5G Customer Premises Equipments (CPEs) positioned around the court, each connected to immersive cameras. These devices capture and transmit high-bandwidth video streams, primarily uplink traffic over the 5G network.

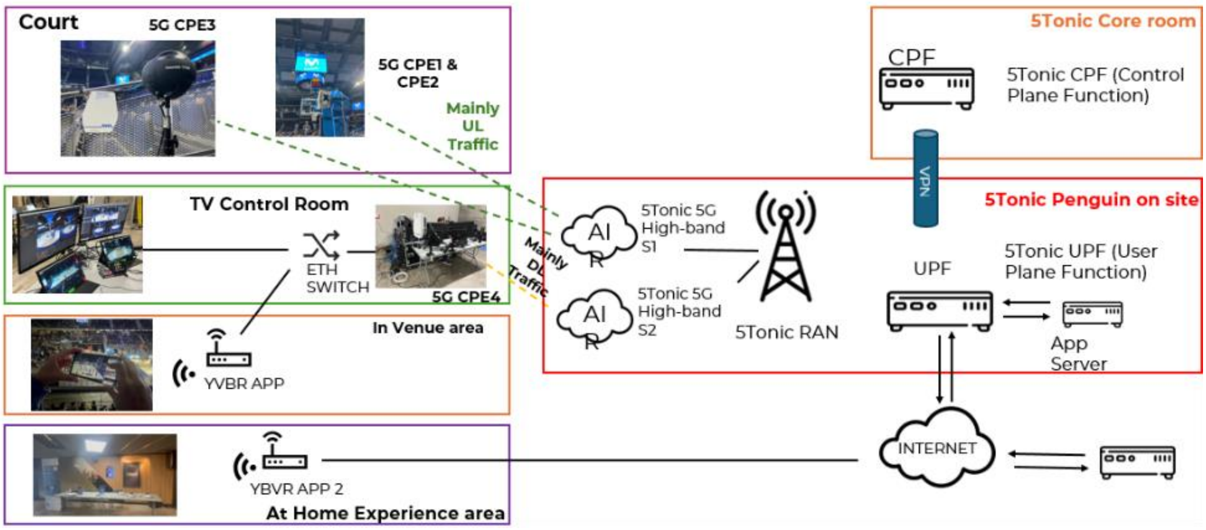

Figure 1. Deployment of four 5G CPEs

The TV Control Room receives these video feeds through an Ethernet switch connected to CPE4. The content is then processed and distributed to the YBVR application, enabling immersive viewing experiences.

On-site spectators can access the live content using the YBVR app via local wireless connections. Meanwhile, remote viewers experience the event through VR streaming delivered over Wi-Fi or internet. The entire system is supported by 5Tonic's [2] core infrastructure, which includes:

- The Control Plane Function (CPF), hosted in the 5TONIC laboratory's 5G core.

[2] https://www.5tonic.org/

- The User Plane Function (UPF), located in the arena's Central Processing Data center (CPD) room, which manages video data routing through the app server and ensures real-time, high-performance delivery via a VPN and internet connection.
  A full description of this use case is available in Annex A.6.

4.2.3. STREAMING CARBON FOOTPRINT TRANSPARENCY

The challenge of becoming carbon neutral within the ICT sector requires concrete actions. To devise solutions in this direction, full transparency of the impacts on the carbon footprint throughout the entire end-to-end chain is required, which translates to a need for measuring and attributing energy usage and carbon footprint at a fine level of granularity (e.g., per user session).

Additionally, most energy efficiency efforts have been encompassed within the network infrastructure, leaving the end-user outside of the loop. Including the end user and providing them with the appropriate information can not only help create awareness of the impacts of different user behaviours and steer them in the right direction but also could help contain rebound effects commonly associated with the pursuit of energy efficiency.

The 'Carbon footprint transparency' use case of the EXIGENCE project[45] proposes the inclusion of metrics such as "Instant Carbon Footprint" or "Total Daily CO2" explicitly during video streaming services (incl. live events), on Over the Top (OTT) platforms, or video conferencing. It is envisioned that this information would be displayed at the top of the screen of the end-user device (next to other indicators such as current time, battery status, or connectivity strength). Building on the availability of this information to create awareness of the environmental impacts each user is responsible for; the end user will have the ability and freedom to adjust the trade-off between the quality of service and the environmental footprint as provided by the ICT system.

Therefore, this use case relies on a series of energy measurements, interoperability between different network domains, AI capabilities and a deeper understanding of the impact of different network nodes/functions on the carbon emission/energy usage throughout the end-to-end chain to unravel the end to end energy consumption (including networks, applications, and devices), as well as the effects particular settings have on energy consumption (e.g., data route chosen, the energy mix where the service is running, as well as the engaged network domains). We conjecture that this necessitates flexible, novel architectural patterns, new modules and interfaces with additional procedures for the overall ICT service measurement, and per-domain energy usage and/or carbon footprint reduction mechanisms.

Example:

User A is waiting for public transportation outdoors and watching a video from OTT B's platform using a smartphone C that is connected to the wireless cellular network of MNO D.

Alternative use case: User A is at home/work and watching a video from OTT B's platform, using a laptop C that is connected via home's/company's Wi-Fi and fixed internet access provider D.

As the video plays, the total end-to-end energy consumption/CO2 footprint for that particular video session accrues, and it is displayed on the top of the screen, as this was the selected configuration for user A. This can be displayed also in a relative manner e.g. assuming a maximum energy /CO2 credit in User A's subscription to MNO D or fixed internet access provider D.

The total end-to-end energy consumption measurements span from User A's terminal to OTT B's platform, including all networks in between.

4.2.4. NETWORKED MUSIC PERFORMANCE

Networked Music Performance (NMP) is the name given to music played live, between remote musicians, through audio over IP technologies, with or without the use of accompanying video. It enables musicians to perform together from different geographic locations. This requires capturing and transmitting audio streams over the Internet (or other backbone VPN networks), which may introduce packet delays, packet losses and processing, as well as capturing and rendering delays that can have an impact on the feasibility of the performance. NMP covers a range of applications from remote auditions, remote music teaching, remote rehearsals and concerts that can take place on a fixed (e.g., concert hall) or in an ad-hoc location (like open air music festivals).

The musicians' performance may be captured by using 360-degree cameras, and this immersive content will be distributed to the audience. Remote spectators, if equipped with VR headsets, will be able to dynamically select their point-of-view and/or follow individual musicians during their performance.

The main challenge for NMP is the latency, as remote musicians cannot play together when they are too much delayed between them. The Audio over IP network and on-site equipment need to provide an end-to-end latency below the maximum of 30 to 50ms. This includes: (i) the delay induced by each local network devices (such as physical/virtual sound card); (ii) the delay due to distance between musicians; (iii) the delay due to the Radio Access Network; and (iv) the delay due to any necessary packet processing, which is challenging to achieve even with today's state-of-the-art 5G technologies. The per kilometre delay between musicians is assumed to be at least 5us for optical fibre (without including switches buffering), while typical sound card delay can be configured to stay below 5ms. This let very few delays possible for each 5G/6G end points.

Within FIDAL project[48], two Networked Music Performance scenarios are experimented: Remote rehearsal for musicians; and Remote musician(s) in a music concert. These scenarios are implemented by using Telenor iCORA network[3], with testbeds located in the city of Trondheim and in Fornebu close to Oslo.

In addition, the HoloFID Open Call funded by FIDAL project[48], and led by i2CAT and Brainstorm, also revolves on how to enable virtual concerts between remotely connected users, between the Telenor (Norway) and i2CAT (Spain) testbeds, represented as realistic holograms and by leveraging virtual production technologies. More details can be found in Annex A.2.

4.3. SMART ADVERTISING

The triangle 6G, AI and IoT enables the vision of ubiquitous computing finally enables the vision of Mark Weiser in his 1991 text 'The Computer for the 21th Century', in which the environment becomes the interface and human computer complementarity facilitates and guides interactions. This could redefine the notion of advertising as something that is not productive and mainly annoying into creating meaningful relations with trusted sources on personal health, resource management and pricing. We envisage a situation of full dynamic pricing, not just on situationally available products like air and train travel and hotels, but on every item in a supermarket, every meal, and every transaction.

The Salesforce State of Marketing report 2024 states that ninety-eight percent of marketing leaders (98%) believe trustworthy data is essential. But, just as the data must be trustworthy, so should its integration with AI. Only 32% of marketers are completely satisfied with how they use customer data to create relevant experiences, and "many marketers are looking to deepen their customer relationships through loyalty programs and omni-channel experiences, but satisfaction is low on these initiatives too."

The main issue - especially among Generation Z and younger - of the tension between data that is seen as advertising and data that is seen as relational and meaningful is strong because of the implicit notion that we should purchase an item or a service that has no meaningful relation with us. That is why citizens do not easily or not at all wish to share trustworthy data. Yet as the industry says trustworthy data is essential.

There is no way out of this dilemma in the current paradigm. However, 6G offers opportunities to balance these tensions in a way that is beneficial to both the industry and citizens.

[3] https://www.telenor.com/insights/creating-the-future/icora-experimental-platform/

In October/November the IEEE Oversight Committee will vote on a proposal called 'Developing a Framework for a 6G Democratic Architecture', an Industry Connections Activity Initiation Document (ICAID)

It proposes a democratic architecture that builds agency on the digital layers ensuring the payments of citizens to architectures (Cloud, edge) applications and services, as well as taxes on these, stay inside of the proposed architecture fuelling maintenance and investments for the public good. For this to happen, we need a starting point. This starting point is a 6G phone that runs Operating System (OS) and Artificial Intelligence (AI) from a secure chip and builds native AI applications, new app stores, open-source services and direct democracy possibilities to vote on topics, no more on parties.

This proposal is inspired by the work of Norbert Wiener, Stafford Beer, Gluhak and Van Kranenburg (2012) and the recent publication: Statecraft and Policymaking in the Age of Digital Twins. Digital Democracy and the Internet of Things (Springer Brief in Political Science, March 2025).

Looking at Europe, it could leverage trillions of euros by the daily use of its 450 million citizens through its own preferred 6G phone device/6G/IoT gateway, router/miner, with its own open-source search, shopping, friends, and messaging services. The architecture could use this consumer device to spill over into Industrial Policy as an IoT Gateway. It could install media wisdom by tuning the image one sees to age or addiction proneness (mental health). It could install the many EU Acts on the phone directly instead of asking for compliance.

6G needs a strong business case to appeal to end users with a meaningful product and SME, Telcos and Industry with a business case. That is the 6G phone. This activity is timely in the debate on sovereignty. Digital Sovereignty, less dependence on Big tech is - especially in Europe - a very serious subject.

This IEEE proposal on developing a 6G architecture is backed by the IEEE SSIT The Standards Committee. Society for Social Implications of Technology is an expert committee developing ethical and sustainable global technical standards to ensure ethical and responsible use of emerging technologies and data.

In this situation new relationships are built that are reciprocal. Citizens have SSI, Self-Sovereign identity. From this SSI one can create disposable identities, pseudonymous identities that can function in the following way. As a renter of a house, I have to pay the energy provider. I send a token saying I can pay (playability). This is all the provider needs (and wants) to know. No data liability on their side, as there is none. If I do not pay, information about me is unlocked from the token, that is only fair as I breach a contract. Any service can function in this way. Advertisers of products and services find their customers on shared apps where citizens expose their wants and needs in a very generic or very specific way. In this way one of the most invasive and potentially productive financial processes - dynamic pricing - can work in favour instead of against citizens. In a 6G environment with full connectivity in retail and backend and full exposure of entities (not full profiles) dynamic pricing will be operating on every item bought in the supermarket, every meal in a restaurant, every beer in a bar.

Such a situation must be harnessed in a framework that citizens find meaningful, logical and sustainable. The key to this situation is trust. If citizens are in a trustworthy symbiotic relationship with their devices and environments, the very notion of advertising removes the negative and invasive connotations as information is targeted and meaningful.

As the nature of advertising itself is changing there will be no more broadcast or narrowcasting that is currently taking place in social media, but companies will be able to create a long-lasting direct communication link with citizens/customers, who will be able to give direct feedback. We can either imagine head displays connected to every personal phone/set of devices, or a particular 'hot spot' in the home that serves the family. 6G allows - as Ericsson has called it an Internet of Senses, gives us augmented vision, hearing, taste and smell. In such a holistic and integrated environment for example cooking could become a joint activity by people at home being guided by chefs remotely.

The most important element in successful adoption is Trust. The potential application and service layer is very rich but also very invasive as it broadens the scope of communications to human senses. What could happen at that interaction end with human actors is extremely rich - in terms of health, training, work and leisure - yet if the technical practical rollout (ten times the nodes of 5G) and device infrastructure is not perceived as trustworthy, these rewards may not materialise.

4.4. HOLOGRAPHICS COMMUNICATIONS

Real-time holographic communications, via 3D holographic representations of users captured in real time, bring the promise to become a dominant social interaction, collaboration, and communication medium in the near future. As reported in recent studies (e.g., Towards socialVR: evaluating a novel technology for watching videos together [57]), availability of realistic video-based volumetric representations of users results in remarkable benefits in terms of levels of embodiment, immersion, co-presence, quality of interaction, and trustworthiness, when compared to avatar-based representations or the usage of traditional 2D videoconferencing tools.

However, the bandwidth, processing and delay requirements also become more stringent than for traditional 2D videoconferencing [21] [22]. Hence, diverse SNS projects are exploring how 6G technologies can contribute to evolving and enhancing use cases revolving around holographic communications.

As a first example, 6G-XR is contributing to such evolution in two separate but interlinked paths. On the one hand, 6G-XR is providing a set of XR technological components to enhance the quality, performance and scalability of XR services, applied to holographic communications, like: (i) advanced multi-sensor capture setups, with dynamic rate adaptation and assisted by Edge processing; (ii) viewport- and distance-aware Edge-assisted delivery architectures; and (iii) Remote Rendering to provide support for lightweight devices [23]. On the other hand, 6G-XR is providing two set of Network-as-a-Service (NaaS)

APIs to enhance the performance and interoperability of holographic communications: (i) network-assisted rate adaptation mechanisms; and (ii) dynamic best Edge selection policies and app lifecycle management features. As a second example, 6G-BRICKS[34] project is effectively integrating holographic communication technologies with virtual production workflows to deliver such experiences to mass 2D audiences (e.g., virtual TV productions to be broadcasted), and integrating semantic communication, in-cloud processing and multimodal interaction features to support collaborative team work activities between distributed holoported users. Finally, SUNRISE-6G is building upon the advances in these two precedent projects to successfully enable adaptive an interoperable holographic communication services across federated inter-MNO domains.

In this domain, the HORSE-6G[43] project[43] also considers an interactive holographic use case for industrial scenarios, by enabling two or more users, regardless of their location, to collaboratively visualize and interact with complex 3D CAD models in a shared virtual environment through avatars. Rendering and computation are offloaded to high-performance servers using Hololight's XR streaming technology, allowing seamless visualization of data-intensive models without compromising quality. This approach demands low latency and high bandwidth for real-time interaction, while also ensuring strict data confidentiality, as the streamed industrial design data is highly sensitive. HORSE addresses these requirements by providing a secure, resilient network with AI-driven cyber threat detection and mitigation, ensuring reliable and protected immersive prototyping sessions for industrial applications.

Similarly, the Unity 6G[32] project addresses a Real-time Holographic Communications use case, which demonstrates how the project's infrastructure enables multi-user XR environments with ultra-low latency and adaptive resource management. Using Hololight Space (an enterprise-grade XR application) streamed via Hololight Stream (a Remote Rendering solution), immersive content is delivered from edge or cloud servers to XR devices, supporting collaborative holographic sessions. An orchestrator dynamically provisions compute and network resources—such as GPU-enabled edge nodes—based on user location and performance requirements. The system continuously monitors bandwidth, latency, and GPU utilization, ensuring smooth experiences through real-time adaptation. This guarantees seamless, high-quality streaming while maintaining energy efficiency. By integrating semantic-aware AI, edge/cloud computing, and advanced orchestration, Unity 6G[32] project provides robust support for demanding XR applications. Potential applicability scenarios include industrial training, collaborative design, emergency response, and border security operations. The approach creates an adaptive, sustainable platform for next-generation immersive holographic communication and collaboration.

The IMAGINE-B5G[33] project**[33]**, a Smart Network and Services (SNS) Project, also aims to implement an advanced, accessible, secure, and programmable end-to-end (E2E) 5G platform for large-scale trials and pilots in Europe by leveraging the best breed of B5G features. Immersive media is one of the verticals that this project actively targets to, and has already enabled several Open-Call projects to explore the interaction between immersive media and 5G networks:

The DEMOCRATS (eDgE platforM fOr dynamiC xR applicATionS) Open-call deployed a true XR multi-user, gaming application, in which a blend virtual and real elements are not only presented to the user, but also interact with each other. The system was designed with novel software components focusing on mitigating varying network conditions in terms of latency and jitter, which is especially important when working over wireless mobile networks such as 5G. Results show that very time-sensitive XR applications as this one can be effectively carried out with proper mitigation components when advanced features such as URLLC are not widely available yet [25].

The BINETHOL (Bidirectional Education System Based on Holographic Cabins Through 5G Networks) Open-call aimed to validate the use of holographic displays within educational environments, using a private 5G network as a base of communications. Preliminary results show that out of 12 subjects, 91% of users preferred holographic lessons over traditional videoconferencing methods (Microsoft Teams) and 75% of users think that it was easier for them to learn with holograms versus traditional videoconferencing methods [24].

The VM4Academia (Volograms for academia) Open-call aimed to validate the use of human holograms inserted on VR and AR within educational environments, using a private 5G network as a base of communications. The key innovation of this project was to perform the full-body human volumetric capture reconstructed with AI from a plain 2D video. Then, these AI-reconstructed holograms could be directly streamed into a multi-platform WebXR application for smartphones, PCs and HMDs running a regular web browser. The results show that users find holograms better for their learning experiences compared to traditional videoconferencing methods. Also, 5G networks prove to be able to carry holograms to the users.

On a smaller scale, several Spanish national pilots are also addressing holographic technologies for media verticals over 5G networks. One example is the collaboration between UPV and Telefónica. These pilots validated high-quality, full-body human volumetric capture to generate holograms for several use cases (education, entertainment and telepresence). Both real-time and on-demand content modes were tested depending on the specific application. The potential of holographic communications over 5G technologies was also tested and validated. The pilots included a VR application for educational purposes with pre-recorded hairdressing, real-time lessons with real students and immersive entertainment experiences with WebXR. The results show that users see a great future and value in holographic technologies for entertainment, education and telepresence, thanks to the high level of immersion and improvement in focus. Also, 5G networks prove to be able to carry holograms to the users [26] [27].

4.5. COLLABORATIVE METAVERSE SCENARIOS

The Metaverse relies on high-quality, multimodal data sources exchanged in real time across distributed entities to deliver rich, interactive, and immersive experiences. It represents a paradigm shift in how humans interact with digital content, the environment, and each other.

As media, eXtended Reality (XR), and network technologies mature, the Metaverse is emerging as a transformative medium for information access, social interaction, and collaboration—going far beyond the limitations of current digital platforms. Its applicability extends beyond media and entertainment to critical sectors such as culture, tourism, education, manufacturing, and healthcare, promising to reshape fundamental aspects of daily life.

To achieve this vision, beyond 5G and 6G technologies become fundamental enablers to address current barriers toward an effective and massive deployment of Metaverse services, including:

- Stringent Quality of Service (QoS) requirements (e.g., ultra-low latency, high bandwidth, and advanced, distributed processing).
- Scalability and interoperability challenges across heterogeneous systems and platforms.
- Ubiquity and reliability, ensuring seamless and robust access from everywhere.

In this context, diverse SNS projects are considering impactful Metaverse-oriented use cases to assess and validate the benefits of incoming 6G technologies. As a first example, 6G-BRICKS[34] project is addressing two Metaverse scenarios. The first scenario integrates holographic communication, virtual production and massive delivery technologies to recreate virtual TV debates, with participation of remote panellists and presenters connected via 6G technologies [28]. The second scenario integrates additional technological innovations in terms of semantic cluster-based communications, orchestration of in-cloud media processing functions, and multimodal interaction features, to enable collaborative group-based team building activities. In addition, SUNRISE-6G project represents a step beyond toward an effective and ubiquitous Metaverse services offering, as it aims to leverage: (i) novel network exposure functions, via standards-compliant Network-as-a-Service (NaaS) APIs, to enhance the performance and interoperability of distributed media services; (ii) an open federation framework to enable seamless, interoperable cross-MNO services across ubiquitous inter-country scenarios.

In addition, the SAFE-6G[47] project is addressing two Metaverse-related use cases, one around an industrial Digital Twin and a second one around Education, to validate its user-centric, trust-by-design 6G architecture that splits the core into User Service Nodes (USN) and Network Service Nodes (NSN). In such a framework, five native trust functions — Safety, Security, Privacy, Resilience, Reliability —are continuously balanced by an AI-driven cognitive coordinator, informed by explainable AI and federated learning, and accessible through an intent-driven conversational interface. More details about the project are available in A.5

Finally, the HoloMED Open Call 3 project, funded by IMAGINE-B5G[33] project, revolves around Collaborate Metaverse scenarios for Immersive Education, integrating live captured holographic representations of users, and a diverse set of shared media playback capabilities to present 2D and holographic videos, and slides presentation in an interactive, personalized and synchronized manner.

5. CHALLENGES AND CONSIDERATIONS

5.1. TECHNICAL SOLUTIONS

Realizing the transformative potential of 6G for the M&E sector requires overcoming technical challenges related to infrastructure requirements, interoperability across complex systems, and security and privacy considerations.

5.1.1. INFRASTRUCTURE REQUIREMENTS FOR THE NEXT-GENERATION M&E SERVICES

Next-generation M&E content, particularly for immersive experiences such as XR, VR, AR, and holographic communications, significantly relies on cutting-edge content capture technological enablers (6G-BRICKS[34], 6G-SHINE[35], 6G-XR[36], ADROIT6G [37], IMAGINE-B5G[33], TeraGreen [38], Hexa-X-II [39] follow this approach). These include high-speed 4K/8K and 360° cameras (3 projects follow this approach), LiDAR sensors (DESIRE6G [40]), and advanced motion, data, and volumetric capture technologies that enable full 3D human body and scene reconstruction (5 projects follow this approach). For instance, visual inspection applications can leverage video cameras streaming up to 50 Mbps and laser cameras at around 5 Mbps, with robot control data packets ranging from 60 to 1300 bytes, and visual inspection packets from 200 to 2kbytes, sometimes exceeding 8 Kbytes (6G-SHINE[35]).

Likewise, volumetric video services like holographic conferencing may require stringent uplink and downlink bandwidth figures, in the order or Gbps (6G-XR[36], 6G-BRICKS[34]). These sophisticated capture capabilities are vital for creating dynamic and interactive virtual presences, enhancing applications in diverse fields such as immersive education, virtual live music production, and industrial scenarios (4 projects follow this approach). Innovations also extend to data processing, where raw sensor data (lidar, camera, and radar) can be reduced by over 97% when processed (6G-SHINE[35]). For XR applications, user head rotation can exceed 360 degrees per second, though typically remaining below 100 degrees per second, and hand movements can reach maximum velocities of 4 meters per second (6GTandem[56]). Furthermore, network-based parameter estimation is being explored to extract information beyond data decoding, such as object localization, with sensing area range increased by a factor of 5 and sensing accuracy by a factor of 2 (Hexa-X-II[39], SUNRISE-6G [41]). The demanding nature of these applications often pushes the limits of existing 5G capabilities, necessitating advancements for future 6G systems (3 projects follow this approach).

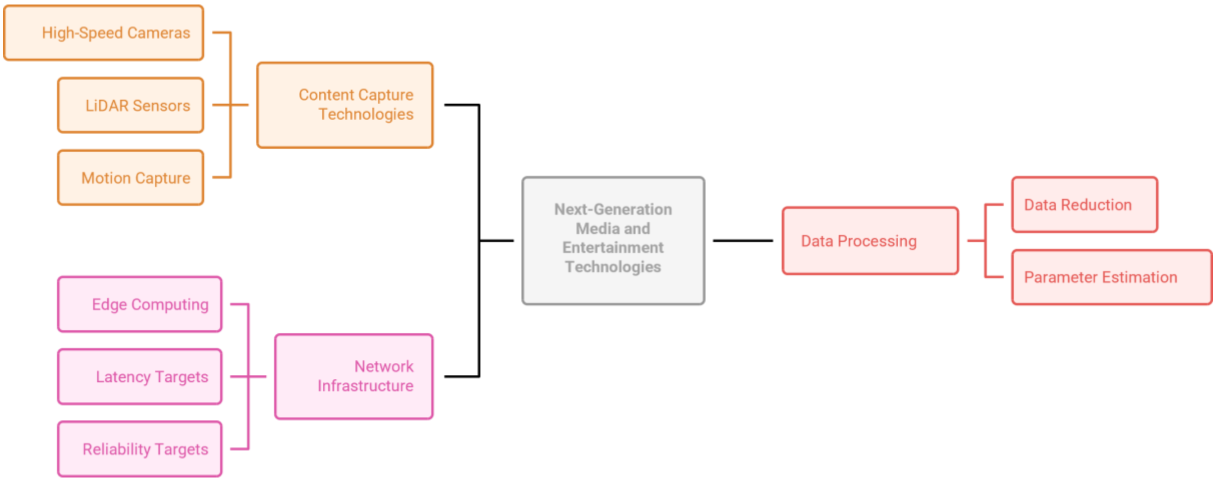

Figure 2: High-level overview of infrastructure requirements.

Immersive experience requires high speed data transmission, especially to deliver UHD image format, such as 4K and 8K resolution, and wide angle. There are many factors which may affect the required data rates, such as video quality and video coding/encoding, including compression. The target streaming data rate for 5G or beyond is expected from 100 Mbps to a few Gbps depending on the required quality and operation. The usage of higher carrier frequency that can provide wideband frequency spectrum, such as sub-Terra Hertz (sub-THz) operating at 100-300 GHz, is beneficial, particularly to deliver high-speed data transmission in a small range (e.g., < 10m) (4 projects follow this approach). The operation of Massive MIMO could enable energy efficient beamforming for sub-THz operation delivering high data rate transmission (Hexa-X-II[39]).

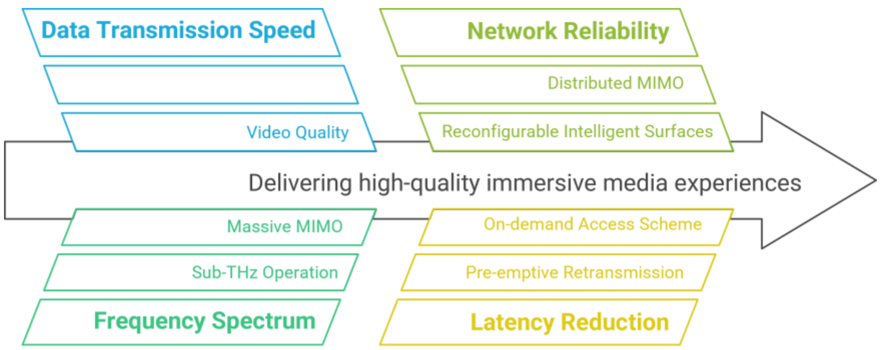

Figure 3: Need for ultra-fast, reliable and low-latency communications.

Distributed-MIMO (D-MIMO), as an evolution of traditional MIMO technology. employs multiple BS/APs cooperate to simultaneously serve a single user. By strategically distributing APs throughout the network, D-MIMO reduces path loss, strengthens signal reception, and lowers the likelihood of signal blockage. Hence, improving the reliability and robustness, particularly at higher frequency (Hexa-X-II[39]). The usage of RIS has also been investigated and proven to improve both capacity and reliability (3 projects follow this approach).

Immersive experience, such as in XR applications, low latency is essential to ensure real-time interaction and responsiveness. A physical layer solution by performing pre-emptive retransmission can provides at least 50% reduction in latency (6G-SHINE[35]). A low-latency sub-THz spectrum access by performing on-demand access scheme configuration, such as pre-configuration of the directed access, can provide a data latency in the range of 100-150 microseconds (Hexa-X-II[39]).

Moving from communication modalities to networking approaches, the underlying infrastructure must be capable of handling the high-volume data ingestion, real-time processing, and storage generated by these diverse sources (8 projects follow this approach). This typically involves significant computation at the edge of the network, leveraging GPU-accelerated edge servers and other programmable accelerators like DPUs and SmartNICs for tasks such as image processing, data fusion, and volumetric media reconstruction and rendering (7 projects follow this approach). Specialized solutions like the Volumetric Video Multipoint Control Unit (VV-MCU) and Remote Renderers are being developed to efficiently mix and transcode multiple user streams, substantially reducing bandwidth and processing demands on the client side while enabling interactive, real-time conversational services with minimal latency (6G-BRICKS[34], 6G-XR[36]). The overarching goal is to ensure ultra-high data rates and extremely low latency to deliver truly immersive experiences and perfectly synchronized operations (6 projects follow this approach). Target end-to-end latencies strive for under 100ms and as low as 5ms for critical applications (4 projects follow this approach), with some targets reaching <1ms (NANCY [46]). Reliability targets often exceed 99.999% (3 projects follow this approach). Network throughput targets can reach 1 Tbps (NANCY[46]), while user-experienced data rates are projected up to 400 Mbps with area traffic capacity around 200 Mbps/km2 (3 projects follow this approach). Energy consumption is targeted for a reduction of over 50% [ADROIT6G] and 30% savings for satellite downlink transmissions (SUNRISE-6G[41]). Operational efficiency improvements include reducing production line update times to less than 20 minutes, diminishing work incidents by 25%, and increasing overall production line uptime by 33% (SAFE-6G[47]). Processing data closer to the source at the edge helps to reduce communication overheads, decrease latency, and enhance privacy by minimizing the need for extensive data transmission to centralized cloud servers (FIDAL[48]).

In order to meet these stringent requirements of future M&E applications, SNS JU funded projects widely adopt distributed and hierarchical edge-cloud architectures emphasizing performance, scalability, and resilience. A common principle observed across many projects is the transition to cloud-native designs and network disaggregation and virtualization, moving away from monolithic systems towards modular components deployed flexibly across far-edge, edge, and cloud domains (5 projects follow this approach). This includes the functional splitting of network elements, for instance, placing gNB-DU on-board non-terrestrial platforms and gNB-CU on the ground for efficient management (5G-STARDUST [49]). Many projects also focus on federating diverse test beds and resources, interconnecting geographically separated facilities to create expansive experimentation environments that can share computing resources, 6G technologies, and even AI models (5 projects follow this approach). This networked approach, sometimes referred to as a "Network of Networks," enables comprehensive testing and validation of advanced applications (SUNRISE-6G[41]). Furthermore, AI/ML integration is a pervasive theme, with AI models deployed at various layers for intelligent management, orchestration, resource allocation, and automation, often driven by high-level user intents to simplify complex network configurations (8 projects follow this approach).

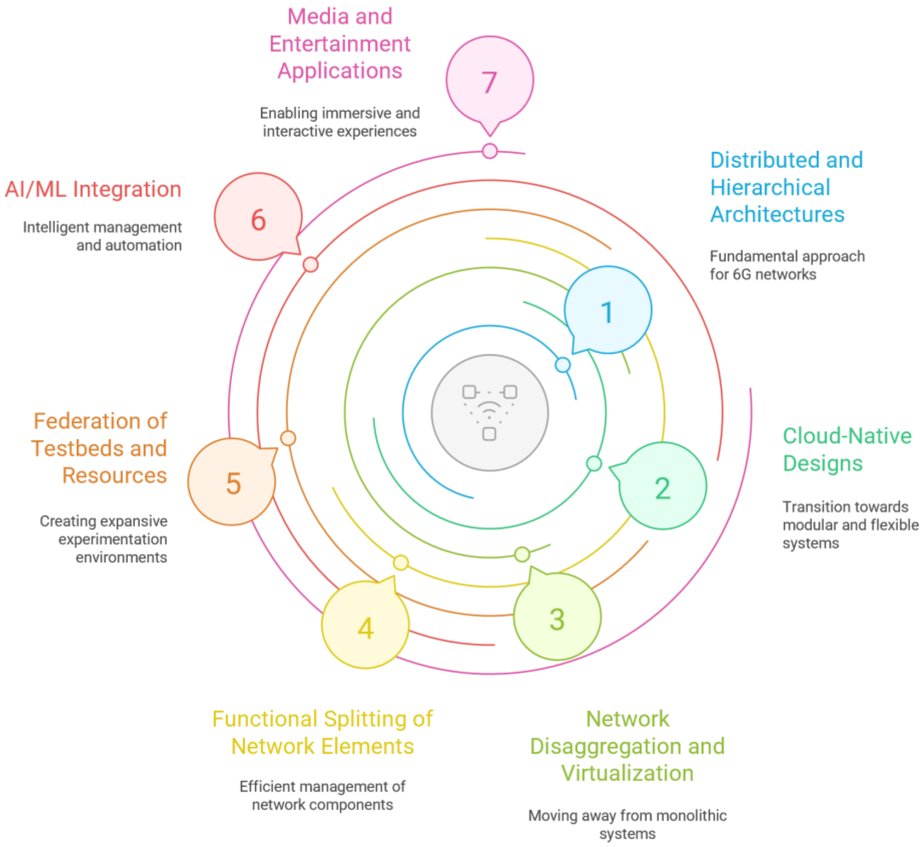

Figure 4: M&E focused network architecture considerations.

The integration of AI throughout the M&E production, distribution, and consumption chain, especially for visually intensive content like video generation and immersive XR experiences, mandates high-performance computing hardware. Projects are developing solutions for real-time video and image processing and data fusion, crucial for applications such as holo-conferencing and advanced volumetric capture (6G-XR[36], 6G-BRICKS[34]), untethered XR for virtual TV shows and multi-user collaboration in virtual team building (6G-BRICKS[34]), immersive education (6G-SHINE[35]), live immersive XR in large-scale events (TeraGreen[38]), and federated cross-domain Metaverse services (SUNRISE-6G[41]). This necessitates powerful processing units including GPUs and leverages other hardware accelerators like DPUs and SmartNICs (SEASON[50]). These demanding AI workloads, along with the growing need for AI model training and analytics, drive the requirement for robust data center capabilities, often distributed across edge and cloud environments to form computing continuums (3 projects follow this approach). For instance, CDNs are being deployed as micro-services across multi-domain continuums (6G-INTENSE [51], SUNRISE-6G[41]) to handle massive data volumes and ensure real-time performance.

Characteristic	AI and Immersive XR Applications	Infrastructure and Hardware	Energy Optimization
Project Focus	Real-time video/image processing and data fusion	Powerful processing units (GPUs, DPUs, SmartNICs)	Developing energy-efficient hardware and software
Application Examples	Holoconferencing, untethered XR, immersive education, Metaverse services	Data centers across edge and cloud environments	AI/ML for resource allocation and carbon-aware service provisioning
Energy Demands	High energy consumption due to visual media processing	Content delivery networks (CDNs) as micro-services	Minimizing energy consumption in network components
Optimization Targets	Monitoring tools for time-continuous energy consumption	Reduction in energy consumption compared to legacy systems	Sustainable radio designs for compact terminals

Figure 5: Energy consumption and optimization considerations

These sophisticated AI workloads, particularly for visual media processing and their extensive infrastructure, lead to substantial energy demands (4 projects follow this approach). Consequently, energy optimization is a critical infrastructure challenge being addressed by SNS JU projects (4 projects follow this approach). Efforts focus on developing energy-efficient hardware and software designs (3 projects follow this approach), including AI/ML-based methods for optimizing resource allocation and carbon-aware AI service provisioning and control (EXIGENCE[45], FIDAL[48]). Projects aim to minimize energy consumption in network components, for example, by putting unutilized transceivers in sleep mode (SEASON), reducing costs by consolidating PLCs within edge devices (6G-SHINE), or focusing on sustainable radio designs for compact terminals with emphasis on power consumption (6G-NTN [44]). Specific targets include achieving at least 30% reduction in energy consumption compared to legacy systems (ADROIT6G[37]) and demonstrating a radiated energy efficacy of 40,000 Tbit/Joule (TeraGreen[38]). Monitoring tools for time-continuous energy consumption measurements (3 projects follow this approach) are also under development to facilitate greener operations and achieve sustainable AI services.

Finally, scalability is a critical aspect of the cloud-native architectural principles and is a core focus of multiple SNS JU projects (6 projects follow this approach). By moving away from monolithic application stacks and adopting micro service-based paradigms, it is possible to decouple services and workflows into smaller, independent, and scalable components. For instance, a video processing pipeline can be decoupled into dedicated services for ingesting, transcoding, packaging, and delivering the video. In this direction, containerization technologies, combined with micro services, provide promising solutions that can efficiently decouple and scale the services on demand. These flexible micro services are orchestrated by platforms such as Kubernetes (4 projects follow this approach). Each micro service runs in its own lightweight container, which can be rapidly replicated, scaled, or removed. If a sudden influx of new content introduces a bottleneck in the transcoding queue, the service orchestrator can automatically deploy additional transcoding service containers. When the demand subsides, these resources are automatically scaled down or removed. As a result, the allocated compute resources are precisely aligned with the demand.

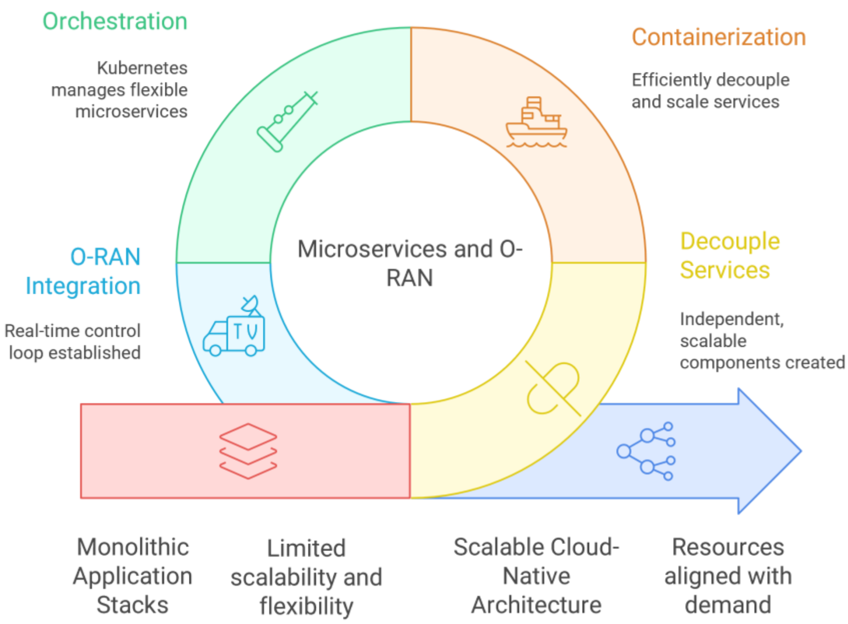

Figure 6: Achieving scalability through microservices and open-RAN.

The creation of a near-real-time control loop between the application layer and the network fabric is an enabler for intelligent and real-time orchestration of the computing and networking resources. The principles of the O-RAN Alliance provide a foundational framework for this by fostering disaggregation of the network entities, along with the definition of the key interfaces for enabling the aforementioned control loop. In this direction, several SNS JU projects have designed and developed test beds and demonstrators that are aligned with O-RAN principles (5 projects follow this approach). In more detail, O-RAN disaggregates the RAN, increasing programmability and integrating intelligence through various components, such as the RAN Intelligent Controller (RIC). This controller provides comprehensive network monitoring and management through different timescales by using O-RAN interfaces to access telemetry data, including user throughput, latency, and resource utilization. These data can be analyzed with AI/ML approaches to provide network-aware resource orchestration. This process also allows for the automated identification and remediation of network issues and bottlenecks, for example, by shifting the network load to less congested cells or scaling micro-services to meet increased demand.

5.1.2. SECURITY AND PRIVACY CONSIDERATIONS

The advancement of mobile networks and the evolution of sophisticated cyberthreats introduce new attack surfaces. Although AI and ML methods are promising assets in detecting and mitigating these threats, their "black box" nature can raise trust issues, especially in critical domains. Therefore, the trustworthiness of AI/ML models is a critical factor that is considered in multiple SNS JU projects (10 projects follow this approach). To this end, eXplainable AI (XAI) provides insights and transparency into the AI models. XAI techniques, provide human-understandable remarks on the model's decisions. For instance, if a network flow is characterized as malicious, XAI can highlight the particular features of the flow (e.g., unusual header length, packet size, or duration of flow) that led to this decision. This transparency is crucial for operators to validate alerts, reduce false positives, and enhance trust in the AI.

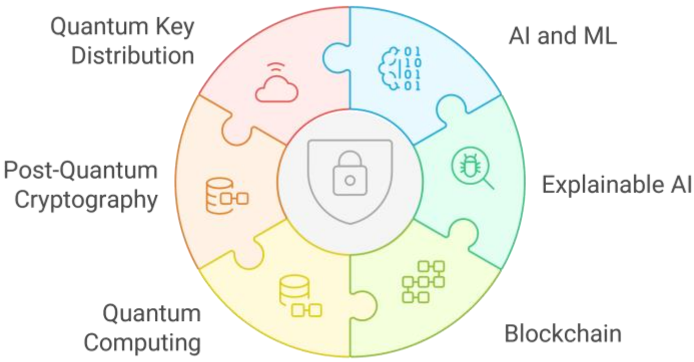

Figure 7: Countermeasures to elevated security risks.

Blockchain is another technology that is being leveraged in various SNS JU projects (3 projects follow this approach). Blockchain provides a decentralized and immutable ledger that can address several security challenges, mainly focusing on trust and integrity among multiple parties. By establishing a Blockchain-based decentralized identity system, each entity manages its own digital identity without a central authority. Service providers encode access rights in smart contracts, creating a secure, auditable, and verifiable method for managing access, while the service consumers can present verifiable credentials to access services without revealing private information.

Moreover, the emergence of quantum computing poses a long-term threat to existing widely-used cryptographic algorithms. As a result, several SNS JU project investigate quantum-resistant approaches to increase network security (3 projects follow this approach). PQC and QKD are key approaches developed in the aforementioned projects. Specifically, PQC focuses on utilizing cryptographic algorithms that are resistant to attacks from both classical and quantum computers. On the other hand, QKD is a hardware-based security mechanism that transmits the key using photons. According to quantum mechanics, any attempt by an adversary to intercept and measure the photons will inevitably alter their quantum state. This alteration can be detected by the legitimate parties, who can discard the compromised key and establish a new one.

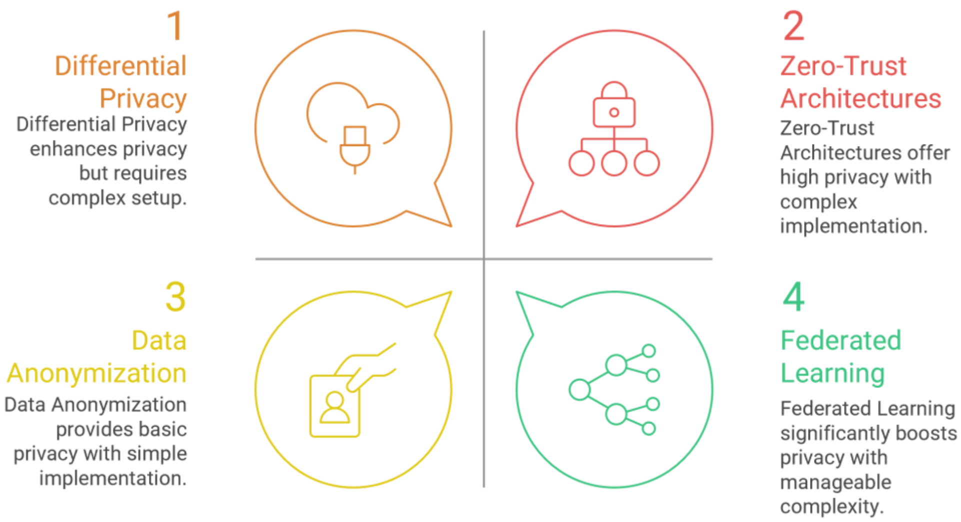

Figure 8: Most adopted privacy preserving mechanisms.

SNS JU-funded projects are already employing a variety of data privacy mechanisms to protect sensitive information in the context of the emerging 6G networks. A widely used data privacy mechanism is Federated Learning (FL), where machine learning models are trained directly on local user devices or across distributed network components, sharing only model parameters or aggregated results, rather than raw user data, enhancing privacy significantly (5 projects follow this approach). Data anonymization and pseudonymization are acutely important data privacy mechanisms shown to be used to protect sensitive data upon collection and processing (3 projects follow this approach). The projects also incorporate Differential Privacy (DP) which adds noise to data during model training so that individual records stay quasi-anonymous whilst still permitting a good level of accurate analysis (Hexa-X-II[39], SAFE-6G[47]). Another well-recognised approach used by projects is Zero-Trust (ZT) architectures that operate on a "never trust always verify" model by preventing access by default and performing fine grained control to stop unintended data access (3 projects follow this approach). Projects deploy Policies and Data Governance (PAG) frameworks to codify rules for data access as well as to support privacy preservation (HORSE-6G[43], SAFE-6G[47]); and focus on processing and computation locally, when possible, to stop sensitive materials from exiting domains in trusted devices (6G-SHINE[35], NANCY[46]).

The topics of data privacy are of significant compare at the M&E vertical in part of the innate complications with the ubiquity of any given content and users contributing to, or interacting with, that content. As part of FIDAL[48] project, for example, FIDAL[48] project quite blatantly demonstrates how “production, storage and unauthorized access to third-party media services can expose sensitive user personal data violating privacy regulations” and that “large media systems may inadvertently disclose intrusive positional and presence data in public population groups causing pervasive safety and dignity risk” [FIDAL]. For use cases such as "Virtual reality networked music performance" it is important that FIDAL prescribes privacy preserving methods for individual communications / movements / interactions (FIDAL[48]). Media and entertainment present a complex and multi-layered environment, and we can map issues of privacy and protecting individual personal data to issues of intellectual property protections and the prevention of access to intentional and unintentional threats, including the need for and importance of encryption, filtering, access rights and remedial measures (FIDAL[48]).

5.1.3. INTEROPERABILITY AND STANDARDIZATION CHALLENGES

The evolution of 6G introduces a diverse and multi-layered ecosystem of network providers, cloud platforms, hardware vendors, and service operators. For the M&E sector, this diversity is expanded by the demands of emerging applications such as XR, holographic communications, and live volumetric streaming, which require ultra-low latency, high throughput, and precise synchronization. Integrating terrestrial and non-terrestrial networks, distributed edge-cloud infrastructures and virtualized network functions into a single, coherent service chain is a complex task. To address this challenge, 3GPP Release 18 introduces the first 5G-Advanced specifications that include significant enhancements for XR applications, including application-aware scheduling, buffer status report improvements, and power optimization features. 3GPP Release 19 will focus on AI/ML-driven communications, TN-NTN integration, and other technologies to bridge the gap towards 6G systems. Finally, 3GPP Release 20 will focus on 6G studies, with Release 21 delivering the first 6G specifications by 2029.

The main challenges include interoperability across proprietary solutions, ensuring consistent end-to-end QoS and QoE (3GPP's QoS framework), securing trust and privacy in multi-party environments, aligning diverse SLAs and enabling dynamic scalability to meet shifting demands, such as during large-scale live events. To address these challenges, common methodologies are emerging around standardized open interfaces like O-RAN, federated test beds for early validation and harmonized orchestration frameworks that unify control across vendors and domains. To address these challenges, common methodologies are emerging around standardized open interfaces like O-RAN, which complement 3GPP standards by defining interoperable interfaces that enable disaggregated RAN architectures with hardware and software from different vendors. These specifications include the open front haul interface (split option 7-2x) between distributed units and radio units, enabling true multi-vendor strategies and reducing operator dependency on single suppliers. Additionally, federated testbeds for early validation and harmonized orchestration frameworks that unify control across vendors and domains are being developed (3GPP Release 19).

Several SNS JU projects are pioneering solutions to these issues at different layers of the ecosystem. Hexa-X-II[39] project lays the foundation by developing cross-vendor enablers such as D-MIMO and RIS, along with standardized protocols for multi-vendor interoperability. SUNRISE-6G[41] and 6G-BRICKS[34] projects extend this foundation through network-of-networks concepts and federated orchestration across domains, while SAFE-6G[47] project introduces trust-by-design architecture to ensure privacy and security. 6G-XR[36] and HORSE-6G[43] projects provide NaaS APIs to expose network capabilities dynamically for advanced XR and holographic services. Real-word validation comes from TrialsNet[55] project, which demonstrates seamless integration across diverse scenarios. In its Immersive Fan Engagement use case, multiple 180° and 360° cameras, a private 5G stand-alone network, cloud-based production systems, and XR end-user devices were orchestrated to deliver ultra-low latency VR streaming during a live sports event. Similarly, the XR Museum Experience showcased how interactive cultural content could be streamed in real-time using private 5G/B5G infrastructure, edge-cloud rendering, and heterogeneous XR devices. These trials highlight the critical role of multi-vendor interoperability in delivering both high-capacity live events and rich, interactive experiences in public spaces. In addition, FIDAL[48] project tackles integration challenges for networked music performance, connecting musicians in different cities using heterogeneous networks, distributed cloud resources and professional-grade audio equipment. Its trials achieved sub-30ms latency to synchronize audio and video streams, demonstrating how multi-vendor systems can enable real-time, immersive performances at distance. Meanwhile, 6G-SHINE[35] project addresses the specific needs of immersive multiplayer XR gaming, integrating XR devices, edge computing nodes and indoor 5G/6G small cells from multiple vendors. The project demonstrates how tactile feedback, visuals and audio can be synchronized in real-time, overcoming interference and network densification challenges in complex indoor environments. Other projects address specialized integration needs: EXIGENCE[45] project for cross-domain sustainability data, NANCY[46] project for RAN interoperability, and TeraGreen[38] project for temporary high-capability THz event deployments. Collectively, these initiatives enable a harmonized, secure, and scalable 6G ecosystem that supports the M&E industry's next generation of immersive experiences.

5.2. SUSTAINABILITY

SNS JU funded projects are adopting comprehensive sustainability approaches, deeply integrating environmental, social, and economic considerations into the design and deployment of future 6G networks. A widely adopted method involves aligning project objectives with the **UN SDGs**, such as promoting sustained economic growth (SDG 8), building resilient infrastructure (SDG 9), and fostering climate action (SDG 13) (10 projects contribute to this action). To measure this impact, projects extensively utilize KVIs, which are designed to assess the broader societal, economic, and environmental effects beyond traditional technical KPIs (11 projects contribute to this action). This dual perspective emphasizes both "Sustainable 6G" (reducing the network's direct impact) and "6G for Sustainability" (enabling sustainability improvements in other sectors) (6G-NTN[44]).

A primary focus for environmental sustainability is **energy efficiency and CO2 emission reduction** (10 projects contribute to this action). Projects aim to measure and optimize power consumption in network components, integrate renewable energy sources, and develop green network architectures (4 projects contribute to this action). For instance, the availability of the end-to-end energy consumption for the video stream demands changes throughout the entire video communication chain. Therefore, stakeholders will need to comply with the requirements to produce and exchange energy consumption-related data and implement them in their respective platforms. These comprise handset manufacturers to include the aforementioned CO2 indicators in their OS; OTT video streaming providers to deliver the information related to their service provision (footprint); MNOs to provide information on their energy consumption and current network architecture (EXIGENCE[45]).

Additionally, **circular economy principles** are being adopted to minimize waste and maximize material reuse by extending the lifetime of devices and installations and ensuring environmentally neutral material lifecycles (5 projects contribute to this action). In the media and entertainment vertical, these approaches translate to reducing the carbon footprint of media streaming by offering "eco-mode" content (EXIGENCE[45]), lowering CO2 emissions from remote holographic communications by substituting physical presence (IMAGINE-B5G[33]), enabling greener production through reduced travel and on-site setups (IMAGINE-B5G[33]), reducing cabling in media production (IMAGINE-B5G[33]), and optimizing energy consumption for XR applications (6G-XR[36]).

From a social sustainability perspective, projects prioritize **digital inclusion** and **improved user experience (QoE)**, aiming to enhance accessibility to services and create more engaging interactions (7 project contribute to this action). Furthermore, **safety, security, and trustworthiness** are fundamental to building public confidence in new technologies, encompassing data protection, resilient systems, and adherence to ethical standards (5 projects contribute to this action). For M&E applications and Services, these efforts translate into enhancing **immersive experiences** for gaming, education, and live music production (6 projects contribute to this action), enabling remote and collaborative content production to increase access and participation (IMAGINE-B5G[33]), improving QoE for XR communications through federated domains (SUNRISE-6G[41]), and fostering social connection and community in virtual environments (TrialsNet[55]).

Economically, SNS JU projects are fostering **new business models and value chains**, often by separating service management from resource management (3 projects contribute to this action). This strategy aims to enable new market entrants, promote open collaboration, and create new market opportunities (6G-INTENSE[51], 6G-SANDBOX [42]). **Cost reduction and operational efficiency** are also key drivers, leading to lower CAPEX/OPEX and optimized resource utilization (3 projects follow this action). Within media and entertainment, this includes creating new services, features, and business opportunities in consumer electronics and content provision (6G-SHINE[35], IMAGINE-B5G[33]), increasing revenue for MNOs and system providers through high-end subscriptions and immersive experiences (6G-SHINE[35], IMAGINE-B5G[33]), and facilitating remote production to reduce operational costs for broadcasters (IMAGINE-B5G[33]). The promotion of a circular economy in in-vehicle subnetworks, relevant for media-on-the-move, also contributes by extending vehicle lifetime and reducing weight and cost (6G-SHINE[35]).

5.3. AI FOR M&E

Artificial Intelligence (AI) has revolutionized content creation across industries by enabling the automated generation of text, images, video, and audio. AI models such as GPT (for language), DALL·E (for images), and other generative adversarial networks (GANs) have drastically reduced the time and cost involved in content production. AI technology is becoming widely used in digital marketing, journalism, entertainment, and education, offering personalized and scalable content solutions. However, the proliferation of AI-generated content raises critical concerns about authenticity, misinformation, intellectual property, and ethical use. Toward this end, the EU AI Act has recently issues guidelines to minimize risks in usage.

AI is not only transforming the way content is created and consumed but is also set to be a cornerstone in the evolution of future communication infrastructures particularly 6G. Its role spans across intelligence, automation, and adaptability, enabling a more connected and responsive digital world. AI is in fact expected to play a foundational role in the design, operation, and optimization of 6G networks, with applications including technologies such as Network Intelligence and Automation, Edge AI and Federated Learning, Semantic Communication, Digital Twin and Spectrum Management,

Several current 6G-SNS projects are already making use of AI technologies, including the following.

- NANCY[46]: The Open Radio Access Network (O-RAN) initiative supports AI-based network automation for high-performance, low-latency, and secure services.

- SEASON[50]: Demonstrates end-to-end Augmented Reality (AR) media services where AI personalizes immersive user experiences.
- 6G-SHINE[35]: Employs AI for real-time interaction and environment recognition in virtual live production and indoor gaming.
- ADROIT6G[37]: Develops AI-driven orchestration and content delivery to support holographic teaching scenarios.
- HORSE-6G[43]: AI assists with behaviour analysis and optimization in multi-user 3D design/review environments using XR.
- 6G-BRICKS[34]: AI can be exploited to predict behaviour in Metaverse-based workplace environments
- IMAGINE-B5G[33]: AI enhances touristic XR experiences through personalization and interactive content.
- FIDAL[48]: Streams real-time music live supported by AI for multimedia synchronization and user engagement.
- TeraGreen[38]: Uses AI to optimize immersive XR experiences in large-scale live events by managing network load and rendering.
- TrialsNet[55]: Uses trained AI agents to interact with visitors of museums.
- SUNRISE-6G[41]: AI can be exploited to optimize multi-user holographic communication services (e.g., edge (re-)allocation, congestion control, data rate recommendation...).

5.4. END USER DEVICES

The advent of 6G will profoundly transform the landscape of end user devices within the M&E sector. As 6G networks promise unprecedented data throughput, sub-millisecond latency, and near-instantaneous responsiveness, consumer hardware will face significantly heightened performance demands. Devices will no longer serve merely as passive terminals for media consumption; instead, they will evolve into intelligent, adaptive interfaces capable of delivering high-quality, highly dynamic and immersive experiences, as explored in 6G-XR[36] project, TrialsNet[55] project, IMAGINE-B5G[33] project and UNITY-6G[32] project. These projects are researching technologies such as volumetric capture, real-time streaming and user interaction to make the end devices more responsive and context-aware.

Conventional devices employed to consume multimedia content, such as smartphones, tablets and smart TVs, will be required to be interoperable with a new generation of form factors, including Extended Reality (XR) headsets, haptic-enabled wearables and holographic displays. These emerging devices are not simply peripheral enhancements, as they are fundamental enablers of the interactive, spatial and immersive multimedia experiences envisioned in the 6G era. Users will not simply visualize higher quality multimedia content, but they will also engage with it through natural modalities such as gesture, gaze and motion, necessitating both hardware and software optimized for responsive, context-aware interaction. In this context, several 6G-SNS projects are working on heterogenous multimedia use cases that integrate the end devices with high quality video capture, real time systems for multimedia streaming and interactions, and networked enablers. 6G-XR[36] project is tackling it at both Core network with the evolution of IP Multimedia Subsystem (IMS), and at the edge computing nodes with the deployment of multimedia functions, i.e., Virtualized Network Functions (VNFs), to support multimedia communications among end devices [5].

To fully leverage the multimedia capabilities, end devices must support real-time encoding and decoding of high resolution and high framerate video, i.e., 8K and 60 frames per second. Furthermore, in the case of XR applications, processing of volumetric content, i.e., complex 3D spatial media including holograms, point clouds and light fields, is needed. This also implies the adoption of volumetric capture technologies, such as depth cameras and Light Detection and Ranging (LiDAR) systems, which enable the realistic digitization of people, objects and environments. These additional components form an integral part of the content ecosystem, facilitating both content creation and consumption. This vision is being validated in 6G-XR[36] project through light-field and multi-camera volumetric capture subsystems [6].

Given the massive data rates associated with improved plain video and volumetric media, advanced compression technologies are indispensable. For the plain video, codecs such as Versatile Video Codec (VVC) and AOMedia Video 1 (AV1) might replace current H.264 and HEVC to achieve increased compression rate. For the volumetric video, emerging volumetric codecs, e.g., MPEG Video-based Point Cloud Compression (V-PCC) and MPEG Immersive Video (MIV) [7] are designed to enable efficient transmission and playback within the constraints of bandwidth and storage. Alternatives codes, based on a wider usage of Artificial Intelligence (AI) also in video coding, might also rises in the next few years [30]. In any case, the usage of new codecs imposes a considerable computational burden, especially for real-time processing on resource-constrained devices. To mitigate this, end user devices will increasingly require dedicated and high efficient hardware acceleration, i.e., Graphics Processing Unit (GPU) and even Neural Processing Unit (NPU) for AI-based codecs, allowing them to stream and render complex spatial scenes without rapidly depleting battery resources.

In parallel, the balance of computational performance with energy efficiency is particularly important for lightweight XR headsets and mobile platforms, where power efficiency and battery life are critical constraints. This is a main challenge also acknowledged in several SNS JU research projects on sustainable 6G systems [8]. Processing-intensive tasks, such as plain and volumetric video compression or rendering, and spatial scene reconstruction, can quickly exceed the processing power and energy constraints of mobile devices. Even with hardware acceleration, sustaining these workloads locally may not always be viable.

Consequently, hybrid architectures are emerging, where the most demanding processing is offloaded to edge or cloud infrastructures equipped with specialized compute resources. The end device, in turn, focuses on interaction management and lightweight rendering. This distributed model, facilitated by the ultra-reliable low-latency communication capabilities of 6G, enables rich and responsive user experiences without compromising device autonomy. Projects such as 6G-XR[36] project [9] and IMAGINE-B5G[33] project [10] are considering remote rendering enablers to process the multimedia content at the edge or cloud nodes such that the required end device processing capacity is minimized. In particular, 6G-XR[36] project provided an overview and analysed most common multimedia protocols to enable remotely rendered content to be consumed by the end device[11]. The results, in terms of the average multimedia protocol latency across different frameworks, are summarized in Table 3.

Table 3: Latency comparison of multimedia protocols for remote rendering

Protocol	Sender framework	Receiver framework	Average latency
WebRTC	Unity Render Streaming (URS)	URS web player	129 ms
Content cell	Unity + GStreamer	gstwebrtc-api web player	253 ms
DASH	Unity + GStreamer	Dash.js web player	10227 ms
DASH	Unity + FFmpeg	Dash.js web player	6519 ms
LL-DASH	Unity + FFmpeg	Dash.js web player	5084 ms
Raw QUIC transport	Unity + GStreamer	GStreamer	293 ms
Media over QUIC (MoQ)	Unity + GStreamer	MoQ web player	194 ms

The assessment used 360-degree video with 1080p resolution at 60FPS, encoded with H.264 at 10Mbps and streamer over a 5G network (3GPP Rel. 15). The findings revealed a significant difference between real-time protocols (WebRTC, Raw QUIC transport and Media over QUIC) and HTTP adaptive protocols (DASH and LL-DASH), suggesting that protocol selection should be tailored to the specific requirements of the M&E application. Furthermore, emerging protocols such as QUIC-based solutions (e.g., Media over QUIC) demonstrated promising results and have the potential to outperform current WebRTC-based solutions once they achieve greater maturity and widespread support in end user devices, as has occurred with protocols such as WebRTC and DASH.

Concerning the access to mobile networks, while conventional devices can easily connect to mobile networks (5G and future 6G), a persistent limitation in accessing mobile networks remains in current generation of XR and wearable devices due to their lack of integrated mobile modems. Most of these platforms rely on Wi-Fi or tethered connections, which undermines the goal of seamless and ubiquitous access to 6G services. As volumetric streaming and real-time interactivity demand high-bandwidth and low-latency connectivity, the inclusion of embedded 6G modems in both capture and playback devices becomes essential. Realizing the full potential of 6G in M&E will therefore depend on the availability of modem-equipped XR and wearable devices that can access advanced network capabilities autonomously.

Finally, the cost of advanced end user devices represents a significant barrier to mass adoption. XR headsets, in particular, remain prohibitively expensive for the average consumer, restricting access to immersive services. Addressing this issue will require targeted efforts to reduce production costs, enhance scalability in manufacturing, and explore new business models to broaden user access and support ecosystem growth. Also in this case, edge computing solutions are envisioned as a possible alternative to reduce the cost of the end device by enabling the current lightweight mobile devices the access to high-performance capabilities without the need for advanced internal processing units. By offloading intensive tasks to the edge or cloud, even today's devices could be adapted to access future media content, bridging the gap between affordable, low-powered devices and the high-demand requirements of next-generation multimedia applications.

TrialsNet[55] project UC10 analyzed the user experience and compared the usage of mobile devices with VR devices in terms of user experience and acceptance. The results, shown in Table 4, revealed that mobile devices can deliver high-quality immersive experiences, comparable to those of VR devices, showcasing the potential of enhanced mobile technologies to rival more expensive VR solutions. Both mobile and VR streaming scenarios demonstrated high user experience and acceptance levels, with scores above 80%, indicating that users not only enjoyed and valued these technologies but also found them practical and easy to adopt. This highlights the strong potential for broader deployment of mobile streaming solutions in immersive media. Additionally, it suggests that while VR devices may seem more technologically advanced from a development perspective, the results of the analysis indicate that something as familiar as a smartphone can deliver an experience that is equal, if not slightly superior, to that of VR headsets. This finding underscores the value of enhancing everyday technologies like smartphones, showing that they can be just as impactful for users and developers as more complex and costly innovations.

Table 4: Comparison between Mobile and VR User Experience

KVI	**KVI descriptions**	**Analysis**	**Results**
User experiences Mobile (in-venue)	Perceived ease of use (PEU), Perceived enjoyment (PE), and Customer Experience (CEX)	Analysis suggests a strong positive correlation between technology innovation (mobile streaming) and User experience, with a significant large effect	Mobile streaming user experience achieved an overall score of 82%
User experience VR (at-home)	Perceived ease of use (PEU), Perceived enjoyment (PE), and Customer Experience (CEX)	Analysis suggests a strong positive correlation between technology innovation (VR) and User experience, with a significant large effect	VR user experience achieved an overall score of 80%
Acceptance Mobile (in-venue)	Perceived ease of use (PEU), Perceived usefulness (PU)	Analysis suggests a strong positive relationship between technological innovation (mobile) and how users accept this technology, demonstrating a significant large effect, with a composite score of 4.2 (84%)	Mobile users reported an acceptance rating of 84% for ease and usefulness
Acceptance VR (at-home)	Perceived ease of use (PEU), Perceived usefulness (PU)	Analysis suggests a strong positive relationship between technological innovation (VR) and how users accept this technology, demonstrating a significant large effect, with a composite score of 4.04 (81%)	VR users reported an acceptance rating of 81% for ease and usefulness

In conclusion, end devices will play a pivotal role in unlocking the promise of 6G for the M&E sector, and enabling advanced applications where multimedia content is not only consumed but can also be interacted with. Their evolution, across multimedia capabilities, connectivity, energy management, and affordability, will be instrumental in enabling the next generation of interactive, immersive, and intelligent media experiences.

5.5. REGULATORY, ETHICAL, AND SOCIETAL CONSIDERATIONS

This section mainly builds on the experience of one SNS-JU project – 6G4Society[31] project [31](hereinafter, 6G4S) – while integrating, where relevant, insights from other SNS-JU projects that explicitly address regulatory, policy, and/or socio-ethical considerations.

Since 2024, 6G4S has been examining the following **core questions**: *How can we describe the relationship between 6G and society? How new connectivity technologies like 6G can be influenced by broader social dynamics, while contributing to shape our cultural and societal framework*? In this section, we address these fundamental questions in the specific context of M&E, from a regulatory, ethical, and societal perspective. The **main objective** is to interpret the current M&E evolving context by combining the main **policy and regulatory environment**—most relevant funding mechanisms, EU law, ethical standards, regulatory requirements, content governance, and strategic visions for virtual worlds—with a sociological and value-base analysis. The objective is to *analyse compliance and other such implications of M&E use cases with the actual EU policy landscape shaping 6G's evolution*.

The M&E sector is often where new communication technologies have very high potential and first reveal their transformative power. Yet, as the rollout of 5G has shown, technical feasibility alone does not capture the full story of innovation. Widespread adoption does not erase societal concerns about how technologies affect our lives. On the contrary, the more they will enter our everyday experiences, the more they will deeply shape and transform aspects of our societal organisation, culture, and behaviour. These transformations shall be acknowledged and steered, becoming object of political debate, regulation, and ethical scrutiny. Issues such as health, education, privacy, disinformation, and the growing influence of large platforms on culture and democracy have all entered the public debate—reminding us that introducing and integrating a new technology in society is never just a matter of technical performance.

With 6G, these dynamics are likely to intensify. Immersive communication and AI-generated media will directly engage with values such as authenticity, inclusivity, fair representation, privacy, security, and well-being, raising pressing questions about how people learn, grow up, live, participate, and feel in a shared culture. At the same time, societies themselves are evolving in what they expect and demand from technology.

In Europe especially, debates on sustainability, digital rights, and responsible innovation show that being technically viable and attractive to users is no longer enough. In order to ensure long term societal sustainability, **what matters in 2025** is not just technology adoption, but also, and indeed, especially, its **acceptability**—i.e. whether technologies align with ethical expectations, reinforce positive social values, and integrate sustainability principles. Our aim is to consider, together with the community developing new connectivity such as 6G, how these questions can guide innovation in Europe. This section does so by examining (1) the European policy and regulatory framework for 6G; (2) communication models; and (3) contents, where values, risks, and opportunities converge. As a result, in (4) we present a dynamic mapping of the interface of use cases with legislative, regulatory, and policy instruments classified by societal value and ethical issue, including points of tension.

5.5.1. EU POLICY AND REGULATORY FRAMEWORK FOR 6G: PRELIMINARY MAPPING

The profound societal transformations linked to the progressive transition towards a digital economy – intensified by the global pandemic – challenges the very foundations of law's role and purpose: the regulation of social relations. The effects of connectivity on society, combined with the persistence of unsustainable development and introduction of new technologies, produce societal consequences that need critical attention. While the new ICT technologies offer many advantages, they may (and often do) also undermine trust, spread misinformation, deepen societal strains and, eventually, polarisation, and widen inequalities.

These outcomes stem in part from the fact that the newest technologies shaping our economies, societies, and at times even public debate, including media, were often created with minimal regulatory oversight, and little consideration of shared ethical standards or societal values, due to little to no awareness of their potential transformative effects on society. It is now becoming clear that the technologies governing our socio-economic relations and common spaces must not only align with applicable legal and regulatory frameworks, but also consider and integrate collective norms and desirable values. The central aim of this sub-section, therefore, is to map policies regulating **how to introduce a connectivity technology that is not only legal by design but also, crucially, ethical and socially sustainable by design**. This raises two key issues: *first, does this require the creation of an entirely new set of norms, laws, and regulations*? Or, alternatively, *can existing frameworks and instruments provide a sufficient foundation for building European 6G technology that is ethical and socially sustainable by design?*

Europe's strategic approach to the development of 6G is embedded in a multifaceted funding, governance, and normative ecosystem. The SNS JU, supported by the EU Commission, Member States (MSs), and industry, is funding a broad portfolio of 6G research, trials, and innovation activities—among them, the 6G4S project explicitly addressing societal impacts of the prospective 6G deployments. Complementing this, the European Electronic Communications Code, along with the Gigabit Infrastructure Act and coordinated radio-spectrum policy, create a regulatory basis for streamlined deployment, cross-border interoperability, and access to critical frequencies—especially the upper 6 GHz band, deemed essential by EU telecom operators for enabling high-throughput immersive services, making Europe competitive in the prospective 6G market and R&D.

To ensure evolving 6G services—including media-rich, AI-enhanced immersive platforms—are inclusive, transparent, safe, trustworthy, and sustainable, providers, researchers, and even SNS JU must navigate a regulatory landscape in an ethically-responsible and socially-aware context comprising the Radio Equipment Directive (for safety and spectrum use), the Data Act (data sharing and governance), the AI Act (ethical AI use), and the Cybersecurity Act (certification of critical systems).

In the recent SNS JU White Paper of June 2025, developed by its Sustainability Task Force, the investigation conducted across SNS JU projects demonstrated the limited engagement of running projects as concerns policy or regulatory issues. To the question *"Is the project engaged in policy and regulatory aspects of sustainability?"* only one project replied affirmatively – with other projects (8) claiming only a "potential", "indirect" or "not explicit" involvement, and a remaining majority of 18 projects (out of 27 who participated in the research for that paper), not answering the question, or replying "no".

Moreover, with the exception of the 6G4S project – that by its nature highly engages with policy and regulatory frameworks, stakeholder networks, and addresses sustainability, societal, and ethical policy aspects – only NANCY[46] and SUNRISE-6G[41] projects explicitly mention alignment with sustainability frameworks. The cited above White Paper shows that even those current sustainability goals-related discussions within the SNS ecosystem are dominated by the environmental considerations – namely, by energy efficiency, due to its relative measurability and compatibility with existing projects endeavours. Overall, no policy and regulatory concerns other than those related to environmental sustainability, are addressed, which opens the door for more endeavours for future research and innovation directions.

To sum up this sub-section, in our opinion, there is already a rich body of legislative, governance, and institutional instruments in Europe to provide a sufficient foundation for building European 6G technology that is generally sustainable, and, in particular, ethical and socially sustainable by design. However, some questions go beyond just regulatory mapping provided above.

In sub-sections 2 and 3, we examine key aspects of network innovation technologies. We aim explore digital immersive experiences, and the construction of digital content through questions that go beyond performance or even environmentally-sustainable design: questions about how technologies may embed cultural stereotypes/challenge cultural norms, and how they affect fundamental dimensions of our experience: extending the body's boundaries in communication, reshaping those between reality and imagination—and thus making a profound impact on authenticity, inclusivity, and well-being.

5.5.2. PARADIGMATIC CHANGES IN MODES OF COMMUNICATION

Future networks will bring major innovations in immersive media, making digital immersion a core element of human communication. AR, VR, and XR will allow users to attend virtual concerts, sports, and cultural events in real time with full-sensory presence, while real-time holographic communication will enable life-sized 3D interaction for meetings, social gatherings, and collaboration. The metaverse will integrate these capabilities, combining high-quality multimodal streams to create persistent, interactive, and richly detailed environments.

As these technologies mature, they will redefine how we access information, interact socially, and experience daily life. Holographic communication could replace video calls, creating deeper presence and emotional links, while social media will evolve toward immersive, interactive content, opening new possibilities for self-expression and community building. The metaverse will become a transformative layer for culture, education, tourism, healthcare, and work, blurring physical and digital worlds.

In such a scenario of technological innovation, it is essential to emphasise the principle that any change in information and communication environments can profoundly reshape civilisation by altering the ontological and epistemological frameworks through which meaning is produced and experienced [13]. The uniquely transformative power of these technologies lies in their ability to operate at the symbolic level, comprising the content we share as well as the modalities and media through which information is exchanged, including codes, sensory capacities, channels, shapes, and processes.

It is therefore essential to examine not only the technical possibilities we pursue but also the values at stake: which aspects of traditional communication and the human condition are being transformed, and what this means for the acceptability of these innovations. Two key aspects of human experience are especially affected: (i) the reconfigured relationship between body, space, and environment; and (ii) the blurring of boundaries between reality and imagination. These are examined below.

The Relationship Between Body, Space, and Environment. Emerging technologies aim for invisible, seamless integration into the environment, progressively transcending the physical constraints of traditional communication devices and becoming "naturalised" in everyday life. In immersive environments, the entire corporeal dimension of the human subject comes into play: distant communication will be no longer limited to text or audio-visual representation but will allow the incorporation of embodied presence, gestures, and sensory cues. This marks an **unprecedented evolution in the human–media–environment relationship**, extending sensory and cognitive capacities while redefining spatial perception and the construction of meaning.

Although increasingly invisible and seamless, mediation does not become absent, nor neutral, continuing to shape how sense-making and interaction unfold [14]. From an acceptability perspective, we must **reflect on to which extent these new forms enhance autonomy and authenticity**, or inversely - increase the risk of emotional manipulation, bodily surveillance, and dependency on immersive environments.

The Boundaries between Reality and Imagination. The traditional divide between online and offline realities has long been considered obsolete [15]. With VR and AR innovations, we will witness a further progressive blurring of the boundaries between physical, digital, and imagined spaces. XR's immersive affordances can create experiences of heightened realism and authentic emotional response, challenging our sense of what is "real" and unsettling everyday security. These dynamics affect not only individual well-being but also social sustainability, raising questions about how physical and virtual experiences are articulated across real and imaginary. The ethical implications are profound: while immersion can enrich creativity, learning, and cultural expression, excessive engagement risks detachment from the physical world and weakens the ability to distinguish mediated from unmediated experience.

This concern extends to cultural industries, especially gaming, where design shapes identity construction, self-representation, social relations, and behavioural emulation. Games exemplify how opportunities and risks are amplified: they can foster exploration, cooperation, and diversity, but also reproduce stereotypes or encourage problematic behaviours. Such transformations carry major social consequences, with implications for sustainability and value governance. Key questions emerge: what risks arise, and which values—autonomy, authenticity, inclusivity, well-being—should be safeguarded as immersive communication and XR becomes central to cultural production and experiences?

A Strategic Vision for Virtual Worlds and the Metaverse. The EU increasingly recognises metaverse and immersive virtual worlds as strategic domains. A European Parliament report [16] calls for a comprehensive, sustainable, human-centric EU strategy integrating XR, game engines, haptics, and VR, supported by Horizon Europe and Creative Europe. In parallel, DG CONNECT has proposed non-legislative tools for open, secure, and values-driven virtual worlds, aligning them with EU principles such as trust, inclusivity, and cultural sustainability [17]. Embedding these directions into 6G-enabled media could anchor innovation in European values and societal legitimacy.

A pivotal issue here is the necessity to address **acceptability**—understood as the capacity to make a technology compliant with legal frameworks in force and aligned with cultural values and norms deemed important in a given society—**as early as possible in design**. Doing so allows values, ethical concerns, and divergent visions to surface in time to shape innovation with awareness. This is particularly crucial in M&E, where narratives, representations, and identities in games and immersive environments directly shape users' sense of self, social identity, roles, interactions, and collective imaginaries.

At this threshold, **we move from the level of communication modes** to that of **content and social change**: from how technologies reshape human experience to how media and entertainment transmit and transform cultural values. Content design does not operate in a vacuum; it mirrors social structures, reinforces or challenges stereotypes, and ultimately determines whether the cultural influence of immersive technologies is harnessed for beneficial, ethically acceptable outcomes.

5.5.3. CONTENTS AND SOCIAL CHANGE

If modes of communication reshape how humans interact with space, bodies, and reality, transforming social dynamics and relationships, it is through **contents** that these technologies more explicitly take on cultural and social meaning.

The narratives, images, and experiences conveyed by media and entertainment occasions may reflect existing social structures, and reinforce or challenge stereotypes. In this sense, content design plays a decisive role in linking innovation with cultural innovation and sustainability; as such, it is crucial to reflect on what criteria we adopt to consider certain contents ethically and socially acceptable.

The case of gaming is particularly illustrative. As one of the most dynamic and profitable industries in the digital economy, gaming not only drives technological development but also acts as a cultural laboratory. Its evolution from entertainment into platforms for socialisation, learning, and identity-building demonstrates the transformative potential of immersive environments. But it also highlights the risks associated to the possible reproduction and consolidation of certain value systems. For decades, video games have been shaped by male-dominated design teams, producing cultural imaginaries where women, LGBTQIA+ individuals, racialised groups were under-represented and stereotyped. Female characters, when present, often embodied hyper-sexualised or passive roles, mirroring broader gender hierarchies [18]. These design choices were not incidental: they reflected the biases embedded in the very structures of the industry.

Analysing the sector from an **acceptability perspective**, the questions that arise do not deal with whether games sufficiently entertain or sell, but **whether they appropriately promote values of equity, diversity, and inclusivity**; or why they do over-expose war-oriented and/or violence-based contents. If immersive environments perpetuate stereotypes, contributing to consolidate in societies controversial narratives about social roles or interaction modalities and behaviours, their cultural legitimacy will remain contested, even if best-seller products. Conversely, **when games allow** players to explore identities, experiment with roles, and encounter diverse representations, giving **richer roles to traditionally excluded categories**, they open pathways for empowerment and social change.

The ethical stakes, moreover, extend beyond representation. Research in media psychology has shown that gaming experiences can influence behaviour. Understanding that influence is still a hot, much debated topic: some have argued that violent games may trigger aggressive thoughts in short term [19] as well as desensitisation to violence, while **prosocial games can foster cooperation and empathy** [20]. Although this literature remains contested, the broader point is clear: **immersive content shapes social norms and values**. The challenge, then, is how to channel the transformative power of immersive environments toward outcomes that resonate with widely shared values such as autonomy, fairness, well-being and sustainability.

AI-generate content raises similar issues. Tools for synthetic media creation, avatar design, or automated storytelling amplify the cultural power of immersive environments. They offer opportunities for creativity, accessibility, and personalisation, but also risks of deep-fakes, disinformation, and the reinforcement of hidden biases. As with gaming, the question of ethical acceptability becomes central: who decides which values are embedded in these tools, and how are these values negotiated across different cultural and institutional contexts?

Taken together, these examples illustrate that the **acceptability of immersive contents** is inseparable from their social impact. By foregrounding values in design, whether through inclusive representation, ethical safeguards in AI-generated content, or transparency in creative processes, developers can work so that immersive media are not just widely used but also recognised as instances where inclusivity, fairness, and transparency enter cultural life, and that designing according to values work to support social sustainability. What is ultimately at stake is not the fate of individual platforms, but how Media & Entertainment in the 6G era could look like and how it could contribute to shaping the values and norms of our digital culture.

Content Governance and Digital Rights in Immersive Media: regulation and ethics. Immersive media under 6G will converge with evolving EU frameworks for content governance and rights. The Digital Services Act (DSA) sets binding obligations for platforms—particularly very large online platforms—to moderate content responsibly, maintain transparency, manage risks, and combat disinformation in digital services. Complementing this, the EU's Copyright Directive (2019/790) extends protections for creators, addressing the "value gap" in digital markets and facilitating lawful data mining and reuse in a controlled manner. These regulations ensure that immersive entertainment environments uphold legal protections for creators and citizens and balance moderation with cultural diversity.

Broader objectives under the Digital Single Market also seek to harmonise rules on audiovisual content, drive cross-border collaboration, and bolster media pluralism and cultural autonomy—linking directly to immersive cultural platforms enabled by 6G. Furthermore, targeted policy action such as the European Media Freedom Act, the Media & Audiovisual Action Plan, and the Code of Practice on Disinformation further strengthen safeguards for media independence, journalist safety, and resilience against harmful content, which remains critical in dynamic immersive environments, expected to get to a new stage with 6G. This corpus of instruments, however, will need to be adapted to the expanding set of affordances enabled by the evolution of media environments; more specifically, it shall be capable to appropriately recognise the new risks that may emerge, as well as promote awareness as to the values that are transferred, promoted, and consolidated in society through M&E contents.

5.5.4. FINAL MAPPING PER MOST RELEVANT POLICIES, VALUES, AND CONCERNS

In sub-section (1) above, we have mapped the most relevant regulatory, policy, governance, and funding frameworks, while in sub-sections (2) and (3) we delved into the most pertinent corresponding ethical, societal, and value considerations that the contemporary M&E involves—in general, and, specifically, in the context of new connectivity, including the prospective 6G development and implementation. As mentioned, our analysis drew mostly, but not exclusively, on the case of 6G4S project.

Overall, for the purposes of Section 5.5, while 6G4S[31] project, by nature and objectives, is highly engaged with the applicable policy and regulatory frameworks, as well as ethical, societal and value dimensions, and actively works towards production of specific evidence-based policy recommendations, considering the few other SNS JU projects, which anyhow address sustainability, as well as security and some other regulations, here will go far outside the scope of this White Paper. Therefore, what we present below is an overview of the most prominent policy and regulatory instruments relevant for the M&E sector, mapped against a number of societal and ethical values that are promoted or protected in there:

1. Value: PRIVACY: **Radio Equipment Directive (RED)**, **Data Act**, **AI Act**, and **Cybersecurity Act** – core regulatory frameworks for safety, data governance, AI use, and security certification, directly relevant to 6G platforms.
2. Value: SECURITY VS. FREEDOM OF SPEECH AND INFORMATION: **Digital Services Act (DSA)** and **Digital Single Market / Copyright Directive** – affecting content moderation, platform governance, disinformation, and rights relevant to immersive media content.
3. Value: MEDIA PLURALISM also linked with IMPARTIALITY/INDEPENDENCE OF MEDIA: **European Media Freedom Act**, **Media & Audiovisual Action Plan**, and **Code of Practice on Disinformation** – policies promoting media pluralism, protection of journalists, and combating disinformation in digital media – so, highly relevant for new connectivity technologies, including 6G.

4. Value: HUMAN-CENTRISM: **European Parliament's Report on Virtual Worlds / Metaverse** – calls for a comprehensive, human-centric, interdisciplinary EU strategy for virtual worlds and immersive environments, including funding via Horizon Europe and Creative Europe.
5. Value: DEVELOPMENT/PROGRESS: **Smart Networks and Services Joint Undertaking (SNS JU)** – funding and governance framework for 6G research and innovation.

6. FUTURE OUTLOOK

6.1. 6G ADOPTION PREDICTION BY THE M&E SECTOR

6.1.1. TIMELINE FOR 6G DEPLOYMENT AND EARLY MARKET UPTAKE

The evolution from 5G Advanced toward 6G will be marked by gradual integration of AI-native, cloud-native, and green-native capabilities into production networks between 2025 and 2030. Most major equipment vendors and operators have now converged on a deployment horizon around 2030, with pre-commercial trials and devices anticipated by 2028. This trajectory is consistent across the latest 6G strategic releases from Ericsson (2024 Spectrum White Paper[58]), Nokia Bell Labs (2024 "Envisioning a 6G Future"[59]), Qualcomm (2024–2025 Path to 6G Series[60]), SK Telecom (2024 AI-Native Network Vision[61]), and NGMN Alliance (2025 Drivers and Vision update[62]). These publications collectively predict that the first commercial networks will emerge at the end of the decade, tightly coupled with 3GPP Release 21/22 and the availability of upper-midband (FR3 6–15 GHz) and sub-THz spectrum blocks. The industry seems to converge on a multi-phase timeline. Table 5 provides an overview of the foreseen evolution timeline from 5G Advanced to 6G, while Figure *9* indicates the projected 6G adoption and M&E market growth.

Table 5: The evolution timeline from 5G Advanced toward 6G

Phase	Period	Key Milestones
Research & Conceptualization	2020–2025	Definition of IMT-2030 requirements by ITU-R and early SNS JU projects. Flagship R&D programs (e.g., 6G-IA SNS projects: **SEASON[50]**, **FIDAL[48]**, **SUNRISE-6G[41]**, **6G-SHINE[35]**); M&E pilots focus on proof-of-concept trials in extended reality, holographic broadcasting, and low-carbon streaming.
Pre-standardization & Trial Validation	2026–2028	3GPP Release 20 and 21 introduce 6G baseline specifications; trial networks combining AI native control, MEC, FR3 spectrum; SNS JU Phase III and IV projects establish pan-European testbeds integrating AI-native, NTN and edge-cloud continuum. Early adopters in sports, live events, and immersive media validate network slicing and ISAC capabilities; KPI/KVI measurements in living labs (e.g., **TrialsNet[55]** M&E use cases).

Pre-commercial Pilots	2028–2030	First 6G test devices and first limited 6G deployments by major operators, targeting premium enterprise verticals, such as M&E. Operator field trials (SK Telecom, Telefonica, Deutsche Telekom); Studios, streaming platforms, and broadcasters test hybrid terrestrial–satellite delivery and AI-assisted content rendering.
Commercial Launch	2030–2032	Service availability in select markets; M&E applications include real-time volumetric content, metaverse-scale interactivity, and personalized AI-driven storytelling.
Mass Adoption & Maturity	2033 – 2035	Widespread integration of 6G into creative production workflows, live performance spaces, home immersive systems and wearables. Global coverage through NTN and energy-efficient edge AI will enable ubiquitous access to high-fidelity experiences.

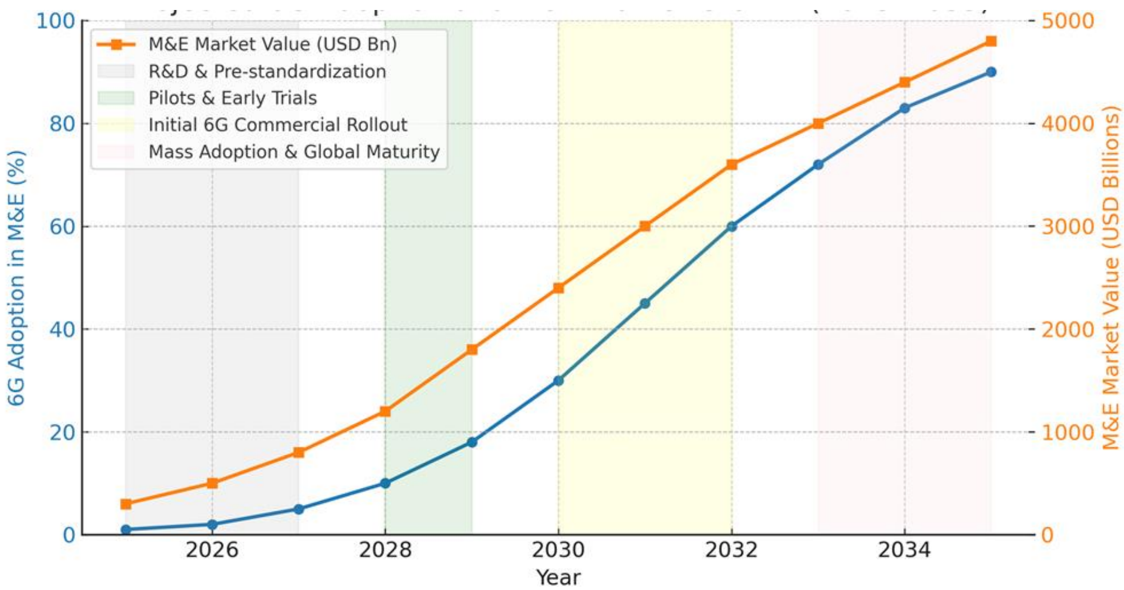

Figure 9: Projected 6G Adoption and M&E Market Growth (2025-2035)

Foundational phase: 5G Advanced features—network exposure APIs, deterministic QoS, network slicing for media production, AI-based RAN management—are being tested in live environments. In Europe, SNS JU flagship projects (e.g., SUNRISE-6G[41], FIDAL[48], SEASON[50], SAFE-6G[47]) are validating immersive-media and holographic-communication use cases. The TrialsNet[55] project UC10 VR Basketball demonstration at Movistar Arena (March 2025) by Telefónica, Ericsson and YBVR proved sub-10ms end-to-end latency and > 1 Gbps uplink, confirming 5G mmWave's readiness for immersive sports streaming and highlighting bandwidth/processing requirements that 6G must address.

Pre-standardization and trial consolidation: 6G testbeds integrating AI in the control plane, joint communication and sensing (ISAC), and semantic compression for media flows will mature. Vendors plan pre-commercial device prototypes (2027-2028) leveraging new spectrum and distributed compute across UE–Edge–Cloud. Operators such as SK Telecom ("6G AI-Native Green Network", 2024[61]**Error! Reference source not found.**) and NTT DOCOMO ("5G-Evolution & 6G White Paper v5.0", 2024[63]) outline edge-AI and sustainability as design pillars, forecasting venue-grade private 6G deployments by 2028 in arenas, studios, and production campuses.

Pre-commercial and early adoption: Standardization under 3GPP Rel-21/22 (2027–2029) and spectrum allocations by CEPT and FCC TAC (2025 reports)[72] will enable first operator-grade pilots. 6G Flagship (Finland, 2025 White Paper on LLMs & 6G[64]) and SNS JU KVI White Paper (2025)[65] anticipate early 6G networks featuring native AI agents managing QoE/QoS across distributed media pipelines. Immersive XR broadcasts, holographic telepresence and synchronized multi-camera production will be trialled in large venues using upper-midband links for uplink-heavy video streams and THz downlinks for real-time rendering.

Commercial mainstreaming: 6G will enter mass adoption for the M&E sector as devices and applications become ubiquitous, cost-efficient, and energy-optimized. Network APIs will enable new business models such as "Quality on Demand (QoD)" subscriptions, real-time sustainability credits, and context-aware advertising. According to industry roadmaps, 6G could deliver 10–100× higher user-data rates, sub-1 ms radio latency, and native trust/sensing functions by 2032, effectively converging connectivity and compute for AI-generated media.

6.1.2. POTENTIAL MARKET GROWTH AND TRANSFORMATION

The M&E sector is expected to be one of the largest economic beneficiaries of 6G. The global M&E market is projected to surpass USD 3 trillion by 2030 (Statista, PwC Outlook 2025[66]), with over 25% of new revenue streams directly linked to immersive and interactive experiences that require 6G capabilities. 6G is expected to inject an additional US $300–500 billion in new revenue streams by 2035 through the emergence of immersive formats, AI-native production tools, and experience-centric services.

6G will not only enhance content delivery but reshape the value chain—from capture to production to consumption. Based on recent white papers and trial data, five sub-segments are expected to capture the largest growth benefits:

1. **Immersive Sports and Live Events**: The TrialsNet[55] project UC10 case (2025) demonstrated that high-definition VR sports streaming can operate at industrial reliability levels when supported by mmWave and edge rendering. Commercial roll-outs by YBVR and FOX Sports during Copa América (2024) validated user readiness for multi-view VR. 6G is expected to expand this market through native multimodal presence—synchronized haptics, spatial audio, and digital-twin replicas of venues—projected to exceed €50 billion by 2032 in Europe alone.
2. **Cloud-Native Production and Remote Collaboration**: Current 5G productions already

offload content editing and mixing to edge MEC servers. 6G will extend this to distributed post-production pipelines with AI co-creation, federated editing, and semantic compression reducing uplink traffic by >70 %. Ericsson's (2024) "Top 6G Use Cases"[67] and Fujitsu's (2024) "Networks in the 6G Era"[68] both highlight smart production as a key vertical. Revenue from remote and virtual production tools is forecast to grow 25 % CAGR 2025–2030, reaching €30 billion globally.

3. **Holographic and Telepresence Services**: Nokia Bell Labs (2024)[59] and InterDigital (2025)[69] identify holographic communication as the defining 6G application. Emerging AI-driven depth coding and distributed rendering will lower bandwidth from tens of Gbps to hundreds of Mbps per stream. Corporate meetings, education, and media interviews will shift to 3D telepresence modes with estimated market size €40–50 billion by 2032.
4. **Metaverse and Interactive Advertising**: InterDigital's (2024) "Network of Technology Convergence" white paper[69] and Qualcomm's "6G Convergence and AI Computing" vision (2025)[70] project a new wave of immersive commerce and metaverse advertising. These will be driven by edge AI, secure identities, and privacy-preserving analytics compliant with EU DSA and EMFA. By 2030, metaverse-based M&E revenues could represent 10 % of the sector's total value.
5. **Generative and AI-Assisted Content Creation**: Edge AI inference on 6G networks will allow dynamic storyline generation, real-time language localization, and audience adaptive visuals. SNS projects (FIDAL[48], SAFE-6G[47]) are already exploring GenAI-in-the-loop media pipelines.

6.1.3. ADOPTION DRIVERS AND BARRIERS

Key drivers for 6G uptake in M&E include:

- Quality-of-Experience (QoE) and latency requirements of immersive media pushing toward AI-native resource allocation and network awareness.
- Demand for sustainability and energy efficiency, as highlighted in Ericsson's (2025) Green Networks report[71] and SK Telecom's "Green-Native 6G" vision[61].
- Open network interfaces and API economies, enabling creative industries to programmatically request QoS and carbon budgets for each production.
- Convergence of telecom and media regulation, with the Digital Services Act and AI Act defining new transparency standards for AI-generated content.

Barriers and uncertainties remain:

- Fragmentation of device ecosystems (XR headsets, holographic terminals) and lack of interoperable formats.
- Capital intensity of 6G-ready venue infrastructure, especially in the uplink path for multi-camera feeds.

- Regulatory clarity on data ownership and synthetic content authenticity.
- Spectrum availability in FR3 and THz bands, with allocation processes still under discussion at CEPT and FCC levels.

6.1.4. STRATEGIC IMPLICATIONS AND OUTLOOK FOR EUROPE'S M&E INNOVATION ECOSYSTEM

For Europe, the M&E domain offers a low-risk pathway to lead global 6G adoption. The combined impact of the SNS JU ecosystem, Creative Europe, and national 6G testbeds will position the continent as a leader in trusted and sustainable immersive media infrastructures. The adoption curve is expected to follow a "dual track" model: enterprise-led early adoption (2028–2032) focused on production and broadcast innovation, followed by mass consumer uptake (2033 onwards) as devices and subscription costs decline.

By 2035, nearly 60–70% of M&E traffic is projected to flow through 6G-enabled networks, supporting high-fidelity, interactive and environment-aware content. 6G will not only enhance the efficiency of current M&E operations but reshape value chains — from content creation to delivery — toward AI-assisted, sustainable, and globally inclusive experiences.

The SNS JU projects provide a unique evidence-based path for early 6G adoption in M&E. By 2027, the expected completion of second-phase trials will deliver validated reference architectures for immersive media, serving as inputs to 6G standardization and ETSI ISG MEC. Simultaneously, national initiatives in Finland, Germany, and South Korea are creating 6G test arenas for holographic events and AI-driven content production. The combination of SNS trial outcomes and vendor/operator roadmaps points to a coordinated commercial ramp-up by 2028–2030, with Europe well positioned to lead in ethical, sustainable, and AI-enabled media technologies.

This analysis is based on the SNS JU experts insights as well as an extensive research on the views and vision of relevant 6G and M&E industry leaders ([58] – [72]).

6.2. LONG-TERM IMPACT ON MEDIA & ENTERTAINMENT

The long-term impact of 6G technology on the M&E sector is expected to be transformative, unlocking current barriers, and bringing significant positive changes as well as new opportunities, as outlined next.

- **Enhanced User Experience**: 6G technology promises to deliver much higher data bitrates, ultra-low latency, and more intelligent connectivity through AI and edge computing. This will enable real-time, high-resolution streaming of immersive experiences without motion lag or latency, such as full-sensory immersive concerts, sports events, and holographic communications.

- **New Opportunities and Innovations**: The advancements in 6G will open up new possibilities for content creation, distribution, and consumption. For instance, immersive and volumetric content capture will allow for the creation of highly interactive and engaging experiences. This will be particularly beneficial for applications such as virtual reality (VR), augmented reality (AR), and mixed reality (MR), where a more immersive experience is desired.
- **Transformation of the Industry**: AI-assisted editing and synthetic media generation will streamline content creation processes, while edge computing will enable real-time content adaptation and low-latency interactions. This will lead to more personalized and engaging content for users. Equally, as AI-generated media becomes mainstream, embedding transparency, authenticity and inclusivity by design will become critical to ensure global trust and compliance with 6G and media regulations.
- **Interoperability & Sustainability**: The deployment of 6G technology will also bring about economic benefits by: (i) favouring interoperability between devices, platforms and networks; (ii) allowing re-usage of available resources; and (iii) optimizing energy efficiency and carbon awareness across the end-to-end multimedia chain; and (iv) reducing deployment and operational costs, making connectivity solutions viable for small and medium-sized enterprises (SMEs) and emerging markets. Interoperability will also encompass a seamless continuity and blending between real and virtual spaces, integrating multimodal content, and enabling multi-network, multi-device, and multi-reality experiences.
- **Social and Cultural Impact**: The immersive and interactive experiences enabled by 6G will have impact on social interactions and cultural experiences. For example, real-time holographic communications will become a relevant medium for social interaction, collaboration, and communication, enhancing the sense of (co-) presence and emotional connection among users.

Overall, the long-term impact of 6G on the M&E sector will be characterized by enhanced user experiences, new opportunities for content creation and distribution, economic sustainability, and significant social and cultural transformations. Ultimately, 6G's long term impact will hinge not only on technological breakthroughs, but on Europe's ability to translate them into sustainable M&E ecosystems - bridging seamlessly interaction and immersion, connectivity and inclusivity.

7. CONCLUSION

The 22 SNS JU running projects have developed and experimented a number of new technologies and use cases addressing the Media and entertainment vertical sector. They are addressing Virtual and augmented reality, Live streaming and broadcasting, advanced sports area media services, immersive fan engagement, Media streaming carbon footprint transparency, networked music performance, smart advertising, holographic communications and collaborative metaverse scenarios.

The main expectation from the M&E vertical sector are **high bandwidth** and **low latency** in order to deliver innovative services with a good quality of experience. M&E applications are also facing **security** and **privacy** issues with regards to fake information and AI generated content. **Interoperability** and **standardisation** challenges need also to be taken into consideration, **sustainability** and **end user devices** are also key topics addressed by the projects. User generated content and remote collaboration are also key applications that will need high quality connectivity.

AI and immersive technologies are more and more used in M&E applications. Such applications need high computing power and high-quality connectivity. 6G is investigating a number of new technologies that could support these technical needs from MEC to RAN.

EU policy and regulation have also a huge impact on M&E applications, a number of regulatory text and societal challenges need to be taken into consideration in order to deliver "clean" M&E applications and services.

This paper is providing an overview of addressed M&E use cases within the SNS JU (including their requirements, target KPIs and B5G/6G added value), as well as some initial results originating from the SNS JU projects. Based on the presented results and the discussed insights, the following key aspects & lessons learned can be highlighted:

- Importance of **Infrastructure for the Next-Generation M&E services** for immersive experiences such as XR, VR, AR, and holographic communications. These include high-speed 4K/8K and 360° cameras, LiDAR sensors, and advanced motion, data, and volumetric capture technologies that enable full 3D human body and scene reconstruction.
- **Security and Privacy are critical issues for M&E services**. User Generated Content especially through Social Networks are sources of fake news, creating significant security and privacy concerns. SNS JU projects have developed a number of solutions based on AI and Quantum that can provide solutions to this challenge.
- **Interoperability and standardization** are key challenges for M&E applications and services. Several SNS JU projects are pioneering solutions to these issues at different layers of the ecosystem. Collectively, these initiatives enable a harmonized, secure, and scalable 6G ecosystem that supports the M&E industry's next generation of immersive experiences.

- **Sustainability** is also a key challenge for the M&E sector. Significant efforts are made by SNS JU projects to address sustainability requirements while enhancing immersive experiences for gaming, education, and live music production, enabling remote and collaborative content production to increase access and participation, improving QoE for XR communications through federated domains, and fostering social connection and community in virtual environments.
- **Artificial Intelligence (AI)** has revolutionized content creation across industries by enabling the automated generation of text, images, video, and audio. AI models such as GPT (for language), DALL·E (for images), and other generative adversarial networks (GANs) have drastically reduced the time and cost involved in content production. With regards to this huge "automatic" generation of content, the future networks need to put in place protections in order to avoid overload, SNS projects are addressing this issue with seral possible solutions.
- **End user devices** are also key elements for M&E sector, devices will no longer serve merely as passive terminals for media consumption; instead, they will evolve into intelligent, adaptive interfaces capable of delivering high-quality, highly dynamic and immersive experiences. Several projects are researching technologies such as volumetric capture, real-time streaming and user interaction to make the end devices more responsive and context-aware.
- **Regulatory, Ethical, policy and socio-ethical considerations** are a core question for M&E applications and services. How new connectivity technologies like 6G are shaped not only by technical performance but also by broader societal dynamics? The 6G4Society[31] project tried to answer this fundamental question in the context of what this means for M&E, from a regulatory, ethical, and societal perspective. The main objective is to integrate the practical policy and regulatory environment—most relevant funding mechanisms, EU law, ethical standards, regulatory requirements, content governance, and strategic visions for virtual worlds—with an analytical framing of immersive technologies and values, M&E including, in order to analyse compliance and other such implications of M&E use cases with the actual EU policy landscape shaping 6G's evolution.

This paper provides also a number of proposals regarding **future outlooks** that should guide the evolution of the M&E sector with regards to connectivity: Several topics are identified such as:

- The timeline for **6G deployment** and **early market uptake**, highlights some dates that could help M&E stakeholders to develop new applications requiring 6G connectivity.
- The potential **market growth** and transformation of the M&E sector is expected to be one of the largest economic beneficiaries of 6G. The global M&E market is projected to surpass USD 3 trillion by 2030 (Statista, PwC Outlook 2025[66]), with over 25% of new revenue streams directly linked to immersive and interactive experiences that require 6G capabilities. 6G is expected to inject an additional US $300–500 billion in

new revenue streams by 2035 through the emergence of immersive formats, AI-native production tools, and experience-centric services. 6G will not only enhance content delivery but reshape the value chain—from capture to production to consumption.

- For Europe, the M&E domain offers a **low-risk pathway to lead global 6G adoption**. The combined impact of the SNS JU ecosystem, Creative Europe, and national 6G testbeds will position the continent as a leader in trusted and sustainable immersive media infrastructures. The adoption curve is expected to follow a "dual track" model: enterprise-led early adoption (2028–2032) focused on production and broadcast innovation, followed by mass consumer uptake (2033 onwards) as devices and subscription costs decline.
- The **long-term impact of 6G technology on the M&E sector** is expected to be transformative, unlocking current barriers, and bringing significant positive changes as well as new opportunities,

In conclusion, **the SNS JU projects reflect a robust and forward-looking agenda that not only drives M&E innovation for 6G but also reinforces Europe's strategic autonomy in telecommunications**. Through its emphasis on collaboration, transparency, and sustainability, the SNS JU provides a strong foundation for Europe's leadership in the global M&E and 6G ecosystem.

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APPENDIX A: DETAILED USE CASE DESCRIPTIONS

A.1 FIDAL project use-case: Advanced sports area media services

Use case: Enriched high quality video content collection and distribution

This scenario considers first the upload of sport event media contents (e.g., UHD 8k and 360° VR) from several professionals or semi-professionals through a video packet pusher application at the end-user device. It is noted that this content is additional to the live streaming video feed of the provider that is typically sent to the broadcaster premises through micro-wave links. The content is streamed live through advanced 5G connection with high availability and upload throughput, utilising techniques such as beamforming to achieve dedicated end-user high-capacity links and extreme upload speed capabilities. StreamSelector Network Application (with both service- and network-level application components) is deployed at the edge or the core and across the continuum, under different load conditions. StreamSelector aims at routing video streams between one source to one or more destinations, while including the capability of processing video (e.g. live transcoding). The application includes the following components:

- a video gateway for receiving multiple video streams and forwarding them to destinations;
- a video stream pusher application, that is used for tests and KPI collection. It streams pre-recorded content like if it was captured live;
- a video mosaic builder for assembling all the collected material, that includes a transcoder for format adaptation and for enabling video preview;
- a stream selector and video player register for managing the end-users, the content to be streamed and technical configurations of User Equipments;
- a Network Application level embedded KPIs collector.

At the receiving end-user site, a video player application is installed and connects to the StreamSelector. Through this, the end user can select which video feed to get and display. This video player application can use professional video interface board for being connected to broadcast equipment.

Use case: Event media content extensions including end-user generated video material

This scenario is an extension to the first one and includes the case of (professional) end-user generated video contents ((P)UGC) to be pushed through the video content management service (i.e., the FIDAL StreamSelector Network Application). Registered end-users have the capability to push video streams with standard quality through the video stream pusher application on their end-devices or the user generated content (UGC) capturing application on their smartphone. The challenge is to identify the system scalability in terms of registered end-users, while at the same time guarantee the quality of the video streams pushed through the first scenario. The workflow using the StreamSelector is the same as before but in this case, the type of end users pushing their content is separated and guarantees are provided according to their type (i.e., high priority for professional end-users, best effort for registered end-users). The video player and content selection application are also adapted to host and provide the additional content. This is followed by related changes required in the video mosaic builder application component as well as the stream selector and video player register component.

The following figure provides the high-level representation for both scenarios, including all the considered deployment and end user options. Considering the first scenario necessary equipment, the following will be added: A (P)UGC application running on Android smartphones that are compatible with 5G SA, that captures and stream live video content. This smartphone app includes a video stream pushing capability, the streams the content of a pre-encoded file, like if it was live content captures from a camera. This feature will be used for being able to get some of the KPIs.

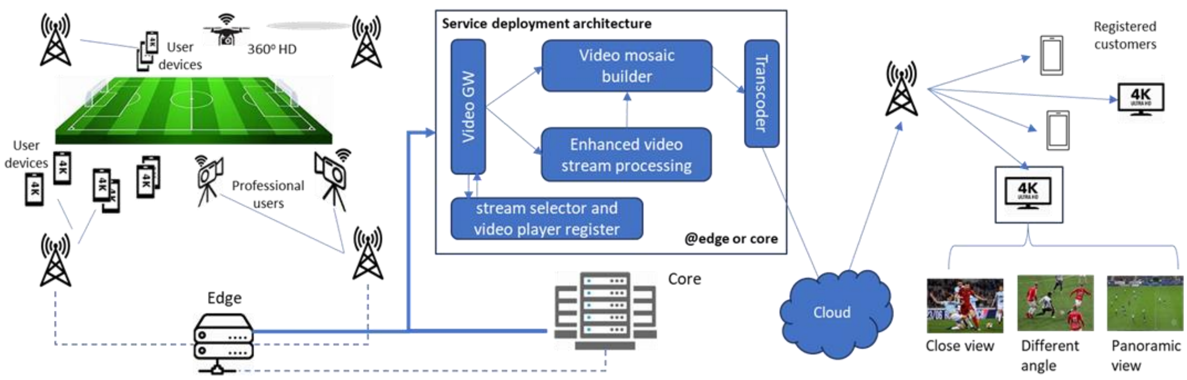

Figure 10: FIDAL project Use Case 4 Workflow diagram

Key to the success of this UC is the integration of advanced features that address the stringent requirements of bandwidth, latency, and scalability for large-scale deployments. For instance:

- **High-Capacity Bandwidth**: enables seamless streaming of UHD and 360° video content, allowing fans to explore multiple camera angles and AR-enhanced replays without interruptions.
- **Ultra-Low Latency**: Critical for real-time video feed processing and AR applications, it ensures minimal end-user-perceived latency, allowing users to experience the content instantaneously.
- **Beamforming and Network Slicing**: These advanced techniques create dedicated high-throughput connections for individual users or groups, ensuring optimal performance even in high-density environments like sports arenas.
- **Edge Computing Integration**: With edge computing, computational tasks such as video transcoding, mosaic assembly, and AR rendering can be processed closer to the user, significantly reducing latency and improving responsiveness

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A.2 FIDAL project use-case: Networked Music Performance

Within ***FIDAL project***, two Networked Music Performance scenarios are experimented: Remote rehearsal for musicians; and Remote musician(s) in a music concert. These scenarios are implemented by using Telenor network, with testbeds located in the city of Trondheim and in Fornebu close to Oslo. The distance between the two cities is of 390 km. To get a maximum end to end latency of 30ms this leaves a maximum of around 15ms for the two testbeds. Each millisecond gained in terms of latency by using 6G enables musicians to be 200km further away. Of course, a very low latency shall be compatible with sufficient bitrate capabilities. When considering audio data exchange between musicians, the need is reasonable regarding even 5G capabilities, but when ultra-low latency video capabilities have to be added it is clearly a technical challenge. Usually, video coding schemes use temporal information redundancy reduction, which use previous and following frames information for coding a current frame. This is prone to generate big delays. Other formats are available such as JPEG-XS, but this requires a large amount of bitrate. Current work in MPEG targeting the Next Generation Video coding (NGVC) is taking into account new requirements, and in them, ultra-low latency, for addressing several use cases such as cloud gaming and XR and metaverse, that should provide solutions in the future for remote musicians to benefit from ultra-low delay video over 6G.

Use case: Remote rehearsal for musicians

Musicians that are not living/present at the same location can occasionally perform rehearsals or practice together with others over the network. They can use technical means such as a sound card and a computer connected to 5G, for being able to share sound with the other musicians. Optionally, they can use their 5G smartphones to stream videos of them playing for better remote presence with the others, while synchronising their music play with the audio from the others. Musicians can use headphones or home studio loudspeakers for the audio rendering. Note that the audio captured by the smartphone is not used in this scenario.

FIDAL Use Case 5.1 large-scale trials involves external musicians being located in two different radio sites. There can be two or more musicians on each radio site, which are not necessarily collocated. As video sources, it is expected at each musician location to use smartphones with a dedicated application or studio cameras, a sound card and a laptop computer connected to FIDAL testbed with a CPE unit. It is also expected to have no concurrent load on the testbed during the trials.

Use case: Remote musician(s) in a music concert

This scenario addresses musicians playing in a concert with remote musician(s) (e.g. as guest(s)). Local musicians on the concert stage are filmed by using professional cameras, and streamed live to the remote musician(s). An Audio over IP network is used for the music play, with musicians synchronising their individual play with the sound coming from the remote musicians.

As an option, the videos from musicians (including 360 video camera) can be distributed to a remote audience, after resynchronisation with audio from the audio over IP network. The remote audience, if equipped with a VR headset, will be able to dynamically select their point-of-view, e.g. following one of the musicians during the performance. Without VR headset, the remote audience will be able to watch regular 2D video content.

FIDAL Use Case 5.2 trials involves (semi)professional external musicians, with a long-distance separation. As an example, a distance of about 400km can be used (such as the distance between Trondheim and Fornebu in Norway), with at least one musician in each location. External audience is able to watch the musicians located on the same place and/or watch it remotely, including by using VR headsets to receive OTT video streams.

A.3 SEASON project use-case: Enabling Next-Generation XR ExperiencesAR

The SEASON project addresses the future of immersive digital services—such as Augmented Reality (AR) and Extended Reality (XR)—by rethinking the foundations of optical network infrastructure. These applications demand ultra-low latency, high bandwidth, and scalable computing, which current networks cannot reliably guarantee. SEASON introduces a new architecture for **self-managed, high-capacity, and energy-aware optical networks**, **designed to meet the stringent requirements of multimedia applications.**

The prominent application examples in this context are Metaverse-driven use cases, where the Metaverse is defined as a 3D, persistent environment where physical and virtual realities merge to enable new forms of people's activities and interactions. Metaverse could be classified into three main categories: (i) Industrial Metaverse, for applications like factory remote operation on machinery and robots, process monitoring and predictive maintenance by digital twins, security control by cameras, robots and drones, virtual R&D, prototyping and testing (e.g., simulation of expensive tests like car crash), healthcare companies performing telemedicine applications, and so on; (ii) Enterprise Metaverse, for virtual co-working spaces/offices and showrooms, virtual meetings and collaboration, virtual recruiting, hiring and on-boarding, professional soft skills or hands-on training as well as enhanced forms of academic learning; and (iii) Consumer Metaverse, for consumers performing, through digital-only or digitally-augmented means, the following activities: immersive social interactions, virtually interactive live music or sport events participation, immersive collaborative cloud-gaming, purchasing a digital asset in virtual stores, and so on; also for citizens exploiting Smart City services provided by Municipalities and Public Institutions, like smart mobility, virtual tourism, security/disaster notifications, etc.

For the specific scopes of the SEASON project, the selected use cases, representative of the three Metaverse categories, described in their service evolution from today support by 5G, medium-term evolution with B5G and final development with 6G, are as follows: (i) for Industrial Metaverse, Tactile Internet for Remote Operation in the context of Telemedicine, specifically Telesurgery; (ii) for Enterprise Metaverse, Academic/Professional Learning, and (iii) for Consumer Metaverse, Smart Tourism in the smart city. The latter use case has been addressed in a specific demo of the SEASON project, as described next.

A Smart Infrastructure for Immersive Services

In a real-world demonstration conducted in L'Aquila, Italy, SEASON deployed a full end-to-end architecture delivering AR/VR content to users equipped with head-mounted displays. Key components included (Figure 11):

- **Multicore Passive Optical Network (PON)**: This access technology enables multiple parallel data channels (spatial lanes) over a single fiber, which can be dynamically activated based on real-time traffic.
- **Software-Defined Orchestration**: A centralized controller, built on SDN principles, coordinates the entire service—from the radio access (5G small cells) to metro transport—responding autonomously to changing user demands.

- **Edge Computing for XR**: The system offloads heavy XR rendering tasks from the user devices to nearby edge servers, reducing latency and terminal energy usage while enabling synchronized multi-user experiences (e.g., virtual museum tours).

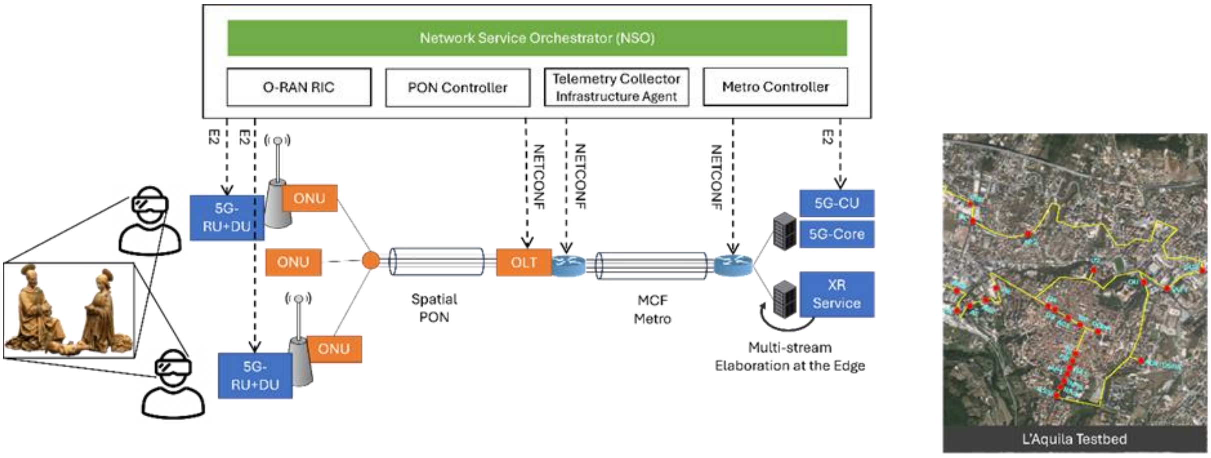

Figure 11: SEASON demo architecture in L'Aquila (Italy)

Intelligent Scaling Based on User Activity

A highlight of the demo was the **real-time adaptation to user load**. When a second XR user connected and requested the same service, the network reacted by:

1. Activating an additional 5G Distributed Unit (DU) and Radio Unit (RU).
2. Opening a second spatial lane in the PON access segment.
3. Provisioning a corresponding IP-over-WDM (IPoWDM) data path in the multi-core fiber metro segment.

This dynamic orchestration ensured that **both users received smooth, low-latency AR experiences** without service degradation—demonstrating how the network can **elastically scale** to match demand.

Technical Achievements in XR Delivery

- **Latency**: End-to-end latency for XR traffic was measured at ~26 ms, with the optical PON segment contributing less than 1 ms—well within acceptable limits for interactive AR/XR.
- **Energy Efficiency**: The ability to deactivate unused fiber lanes and transceivers led to energy savings of ~4% in a small-scale test. Though modest, this proves the

feasibility of **energy-aware spatial resource control**, especially when scaled to larger deployments.

- **Application Layer Integration**: The XR service supported multi-user sessions with roles (guide and visitors), real-time asset manipulation, and synchronized viewing—all controlled through a lightweight Python server with REST APIs and TCP sockets.

The key performance indicators and the results achieved are summarized in Table 6.

Table 6: Key Performance Indicators and Results achieved in the SEASON demo

Metric	Result	Significance
End-to-end latency	~26 ms total (0.6 ms in PON segment)	Compliant with AR/XR responsiveness requirements
Energy savings	~4% (dual-lane, single-OLT test)	Achieved via dynamic activation of spatial lanes
User-driven scaling	Fully automated (DU, spatial PON, metro)	Real-time service adaptation based on actual user activity
XR session capacity	Multi-user, multi-role	Supports synchronized AR/VR for guides and multiple visitors
Control interfaces	NETCONF, REST, OpenConfig, Kafka	Based on open, standard-compliant interfaces
Orchestration	End-to-end via SDN (TeraFlow + RIC + PON)	Full automation across access, metro, and edge domains

Toward the Future of Multimedia Networks

SEASON demonstrates that next-generation XR services are not only technically viable but also **efficient and sustainable** when supported by intelligent optical transport. By combining real-time telemetry, automated orchestration, and spatial fiber multiplexing, SEASON sets a blueprint for how networks can adapt to the demands of future immersive media—scaling performance without scaling energy consumption.

A.4 6G-SHINE project use-case: Indoor Interactive Gaming

The 6G-SHINE project aims to pioneer the main technology components for wireless in-X subnetworks, short range low power radio cells to be installed in entities like robots, vehicle, production modules, classrooms, for a wide set of applications, including those with extreme requirements in terms of latency, reliability, or data rates. Such technology components will leverage the opportunities offered by short range communications and connectivity with a broader 6G network, for providing disruptive cost-effective solutions to deal with major challenges such as signal blockage, interference due to densification, and proneness to malicious attacks.

Subnetwork operation in an entity (in-X) is deployed in all 6G-SHINE use cases. Three subnetwork categories are considered namely the consumer, industrial, and in-vehicle subnetwork categories. Indoor interactive gaming is one of the use-cases in the consumer subnetwork categories which will be highlighted in the following section.

Use case: Indoor Interactive Gaming

This use case is about XR interactive gaming in an indoor environment where one or more players play in a controlled environment. A controlled environment is a place equipped with some equipment to facilitate the XR interactive gaming. For example, various sensors and actuators have been placed in certain strategic locations, the high capability element acts a similar function as access point and its antennas are placed in optimal location, and a high-end edge server is located or attached together with the HC. A controlled environment is likely an indoor area / a room dedicated for this use case. Figure 12 illustrates the scenario of indoor interactive gaming within a subnetwork. Here, there are two game players, each of them is wearing various types of devices:

- VR headsets
- small sensor and actuator devices attached to the body.

The tracking of headsets could be both outside-in or inside-out, where the outside-in tracking is the external sensors (like base stations) placed around the VR headset to track the movement of the users while the inside-out tracking is the embedded sensors (like cameras) placed on the headset or controllers to track the movements of the users. Based on the setting of the indoor environment, the outside-in type tracking is more suitable for this scenario.

The indoor environment is equipped with many static sensor devices which are scattered around the room. These sensors are used to obtain user(s) poses / orientations and then later to be used for the XR scene generation. All those sensor devices can communicate locally to an HC within a subnetwork. There is also an edge server that can be built-in to the AP or separately.

The game, obtained from the application cloud server, is preloaded into the edge server. The edge server provides the XR scene to the VR headsets based on the input from the camera attached to the VR headsets and various sensors (e.g., in the VR headsets, attached in the room, and attached to the users). The XR scene can be produced in the edge server so that it will minimize the computation process in the VR headsets itself. This process is known as split-rendering operation. There are also another options where the VR headset has high capability computation so that the XR scene can be self-generated. However, it may also increase the VR headset power consumption.

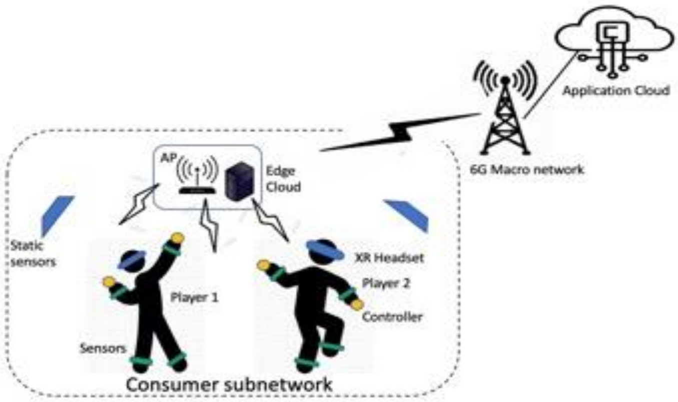

Figure 12: Illustration of indoor interactive gaming within a subnetwork

In order to provide immersive XR experience, the edge server could provide input to the device attached to the users (i.e., actuators) so that the game player experiences sensation of the game in a form of, for example, vibration, heating. This sensation inputs shall be synchronized with the XR scene delivered to the game player. Furthermore, the XR experiences (e.g., XR scene, sensation) shall also be synchronized among all the game players.

An architecture diagram for the indoor interactive gaming use case is shown in Figure 13. In this figure, we consider two users equipped with XR devices (e.g., headset). One XR device is represented as a High Capability (HC) element. The XR device has high computation function so that it can locally generate the XR viewport rendering based on its own sensor and controller input. The sensor and controller can be in a form of SNEs. The other user is equipped with an XR device as a Low Capability (LC) element. It does not have high computation function so that it performs split rendering process in order to generate the XR video at the game player display. The LC receives the sensors' and controllers' information from SNEs attached to the game player. The information is transmitted by LC to the AP (another HC element). HC element that has AP functionality here has even higher capability than the HC for XR device. It performs various roles such as gateway role, RRM role, offloading role. The offloading role would enable the AP to perform as XR engine to generate the XR scene for the XR device with LC element. The HC as an AP is also connected to other XR devices with HC elements, SNEs representing sensors, controllers, and actuators. The HC can be connected to a 6G BS, that can manage radio resources among other subnetworks. The 6G BS is connected to the CN as well as to a CompN, that can take care of computational tasks related to the resource management of the subnetworks in the coverage area of the parent network. The subnetwork can also optionally be equipped with a RIS element to improve the signal reception in certain areas.

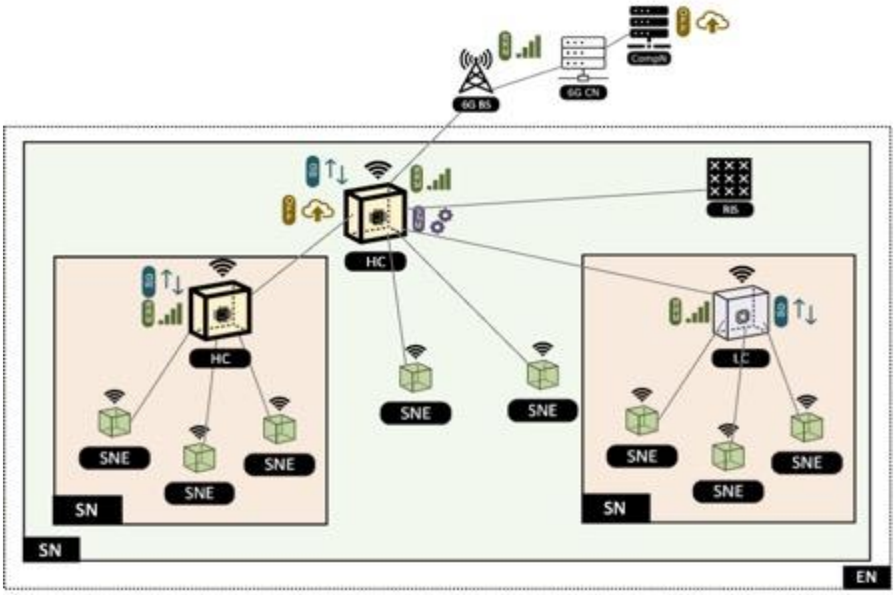

Figure 13: Subnetwork Architecture of the Indoor Interactive Gaming Use Case

Challenges to the 6G system

The XR interactive gaming as described above requires massive communication links between the sensors and the edge server, XR scene processing, and the transmission of XR scene from the edge server to VR headsets and devices attached to the users. All of these operations shall be executed in a very limited time in order to provide a high quality XR experience. The main challenges are:

- To provide various sensors outputs from multiple nodes in a synchronized manner
- To provide the scenes and information for different users in a synchronized manner
- To provide ultra-low latency and high reliability communications
- To provide high data rate communication (i.e., providing XR scene to the users)

The above challenges may not be fulfilled by the existing 5G technology. A 6G system with subnetwork operation is expected to overcome those challenges. A subnetwork that is operated within a close proximity (less than 10 meters) can ensure extremely low latency and high reliability communications, particularly for high data rate communications. The usage of RIS is expected to have an important role in increasing the performance of radio communications. The RIS panel(s) can be strategically placed in certain locations of an indoor XR gaming area.

The following highly relevant technology components (TCs) are considered for this use case.

Table 7: Key TCs for Indoor Interactive Gaming Use Case

Technology component (TC)	Explanation
Sub-THz system models	Indoor gaming, especially in small room, makes it feasible to operate the wireless communications with sub-THz frequency in order to provide high data rate and ultra-low latency communications.
Ultra-short transmissions with extreme reliability	Ultra-low latency with high reliability improves the user experience.
Analog/hybrid beamforming/beamfocusing	Enable optimized communication with individual devices or groups of devices within the coverage area of a particular subnetwork and at the end the overall network capacity.
RIS enhancements	Enable reflecting radio signals towards individual users within a room
Hybrid management of traffic, spectrum, and computational resources	Enable the efficient resource allocation and distributing the computational resources in various nodes.

A.5 SAFE-6G use cases: Metaverse Pilots for Industry and Education

The SAFE-6G project is pioneering a user-centric, trust-by-design 6G architecture that redefines how media-rich services are delivered and safeguarded across the edge–cloud continuum. By splitting the core into User Service Nodes (USN) and Network Service Nodes (NSN), SAFE-6G enables per-user instantiation of network functions and trust policies. Five native trust functions — safety, security, privacy, resilience, reliability — are continuously balanced by an AI-driven cognitive coordinator, informed by explainable AI and federated learning, and accessible through an intent-driven conversational interface. This approach is particularly relevant for the media vertical, where immersive experiences, sensitive personal data, and heterogeneous device ecosystems converge.

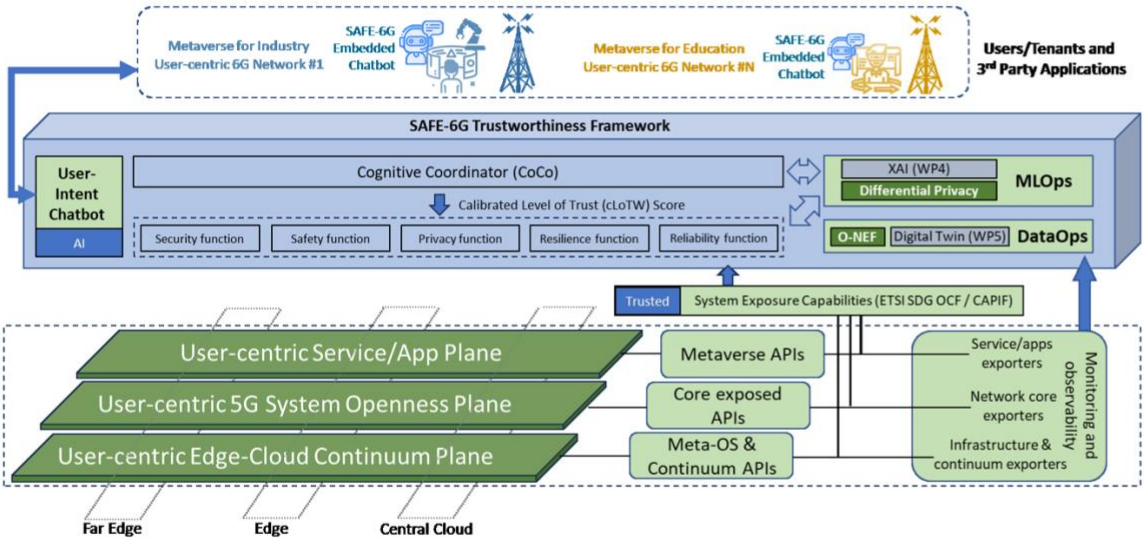

Figure 14: Overview of the SAFE-6G technical architecture.

To validate its framework, SAFE-6G is deploying two metaverse-based pilots on a small-scale but fully operational prototype infrastructure. These pilots deliberately push beyond conventional VR/AR headsets to integrate novel sensing and capture devices such as biometric-aware Reverb G2 Omnicept, high-precision haptic gloves, and the Perception Neuron 3 Compression Suit for full-body motion tracking. This rich sensorium enables deeply interactive, media-intensive environments — ideal stress tests for the SAFE-6G trust and performance capabilities.

Use Case 1: Industrial Metaverse for a Production Line

Built around a Digital Twin (DT) of an industrial production line, this pilot explores how XR + AI services can enhance situational awareness and decision-making. Workers and managers can visualise AI-generated adaptations to workflows, reschedule machines and staff in response to emerging issues, and collaborate remotely in updating the DT. Given the sensitivity of factory data and the potential safety implications, Level of Trust (LoT) management is paramount. The deployment adopts an on-premise-centric architecture for security, while leveraging platforms such as NVIDIA Omniverse to manage complex 3D scenes. SAFE-6G will evaluate how its trust functions safeguard operations without hindering agility.

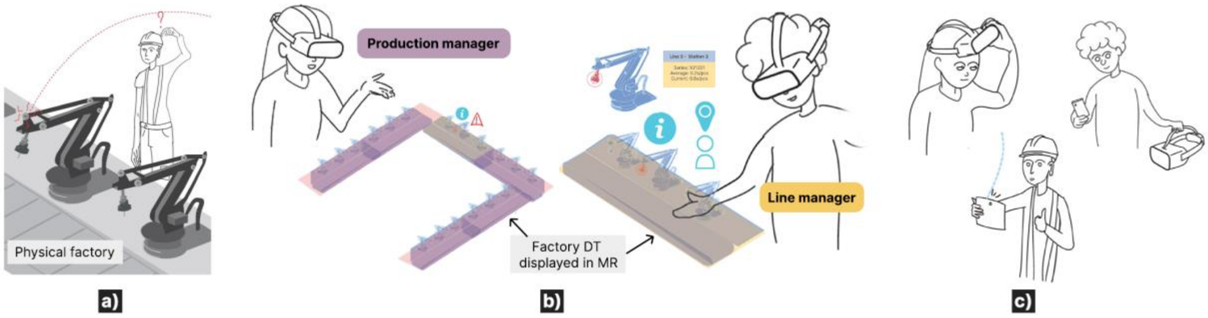

Figure 15: SAFE-6G first use-case scenario, based on an industrial digital twin metaverse application.

Use Case 2: Metaverse for Education

This pilot examines 6G's ability to support persistent, hybrid XR classrooms that blend co-located and remote learners. Originating from IMM's work on collaborative learning spaces, the environment aims to maximise presence and real-time interaction, augmented by XR + AI conversational agents to assist teachers and personalise learning. Technical challenges include orchestrating a wide array of heterogeneous devices — from AR/VR headsets to projection systems and tablets — many of which have limited native compatibility with 5G/6G. Strong authentication and protection of personal, emotional, and behavioural data are critical. SAFE-6G's distributed edge/cloud architecture, integrated with XR assets and Sharing collaboration software, will be tested under varying deployment and trust scenarios.

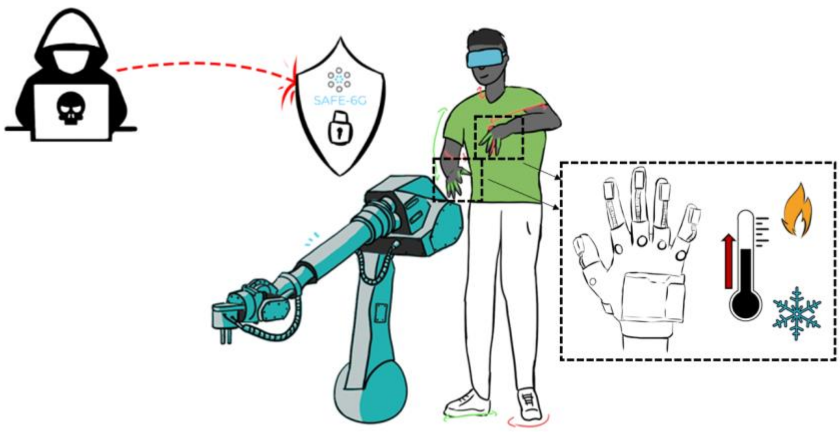

Figure 16: SAFE-6G second use-case scenario: example of potential cyber-physical attack during an XR formation session.

Relevance to the Media Vertical

Both pilots embody the media vertical's trajectory toward immersive, interactive, and collaborative experiences that demand ultra-low latency, high reliability, and assured trustworthiness. By embedding security, privacy, and resilience directly into the network fabric — rather than as bolt-on afterthoughts — SAFE-6G offers a blueprint for delivering next-generation media services at scale. The outcomes will inform not only technical standards and deployment models, but also policy and regulatory frameworks that balance innovation with protection in Europe's digital media ecosystem.

A.6 TrialsNet use case10: Immersive Fan Engagement

TrialsNet UC10 successfully delivered a virtual reality live broadcast of a basketball game leveraging YBVR´s (https://ybvr.com/) immersive streaming technology, deploying 180° and 360° cameras strategically positioned around the basketball court. These cameras were connected to the production system and seamlessly transmitted immersive live video feed over B5G stand-alone network installed within the stadium.

The use case featured two distinct scenarios:

- **In-Venue experience**: Users receive multi-screen information on mobile smartphones, allowing them to select different TV feeds in real-time. This scenario requires low latency, precise geolocation, and optimized downlink to serve video feeds to numerous smartphones within the venue.
- **At-Home experience**: Users access the sports match via VR headsets, with cameras positioned court-side providing a seamless immersive viewing experience.

The final match took place on 16th of March 2025 during a basketball match of Movistar Estudiantes vs Súper Agropal Palencia at Movistar Arena, Madrid. The diagram in Figure 17 illustrates the deployment of four 5G Customer Premises Equipments (CPEs) positioned around the court, each connected to immersive cameras. These devices capture and transmit high-bandwidth video streams, primarily uplink traffic over the 5G network.

The TV Control Room receives these video feeds through an Ethernet switch connected to CPE4. The content is then processed and distributed to the YBVR application, enabling immersive viewing experiences.

On-site spectators can access the live content using the YBVR app via local wireless connections. Meanwhile, remote viewers experience the event through VR streaming delivered over Wi-Fi or internet. The entire system is supported by 5Tonic's (https://www.5tonic.org/) core infrastructure, which includes:

- The Control Plane Function (CPF), hosted in the 5TONIC laboratory's 5G core.
- The User Plane Function (UPF), located in the arena's Central Processing Data center (CPD) room, which manages video data routing through the app server and ensures real-time, high-performance delivery via a VPN and internet connection.

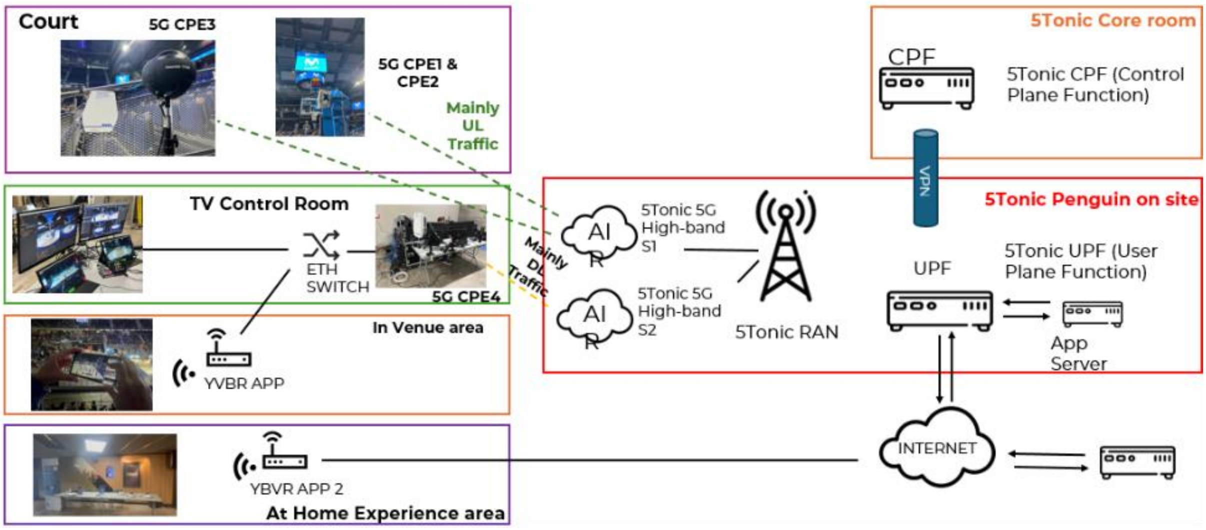

Figure 17. Deployment of four 5G CPEs

During the execution of the final UC10 trial in the TrialsNet project, two distinct scenarios were carried out to evaluate system performance under different usage conditions. The in-venue scenario was implemented inside the arena, with the test activities located in the upper deck seating area (Figure 18). This setup was intended to simulate user experiences and network demands from spectators physically present at the event, allowing measurement of connectivity quality, latency, and throughput in a dense, high-capacity environment.

In parallel, the at-home scenario (Figure 20) was executed in a separate location within the same venue complex, specifically in the hallway outside the court area. This configuration was designed to replicate the conditions of remote viewing or off-site user engagement, even though it remained within physical proximity to the arena. The separation between the two testing zones ensured that data could be collected independently for each use case, enabling a comparative analysis of network behaviour, service quality, and user experience across the two contexts.

Figure 18. Actual image of in-venue scenario

Figure 19. Actual image of at-home scenario

Based on the final field test, the table below (Table 8) summarizes the measurement results and validation status of the final KPI tests for each test case. It compares the expected KPI targets against the actual measurements to confirm compliance.

Table 8. UC10 KPI Results

Test case ID	KPI description	Test requirement	Measurement result	Validation
CPE1	KPI#01 Downlink throughput per user:	0.5 Mbps	0.902 Mbps	OK
	KPI#02 Uplink throughput per user:	30 Mbps	28.72 Mbps	
	KPI#08: Application round-trip latency	10 ms	6 ms	
	KPI#017: Service availability	99.99%	100%	
CPE2	KPI#01 Downlink throughput per user:	0.5 Mbps	0.91 Mbps	OK
	KPI#02 Uplink throughput per user:	30 Mbps	28.75 Mbps	
	KPI#08: Application round-trip latency	10 ms	6 ms	
	KPI#017: Service availability	99.99%	100%	
CPE3	KPI#01 Downlink throughput per user:	1 Mbps	1.595 Mbps	OK
	KPI#02 Uplink throughput per user:	90 Mbps	87.42 Mbps	
	KPI#08: Application round-trip latency	10 ms	5 ms	
	KPI#017: Service availability	99.99%	100%	
CPE4	KPI#01 Downlink throughput per user:	220 Mbps	215.14 Mbps	OK
	KPI#02 Uplink throughput per user:	70 Mbps	64.09 Mbps	

	KPI#08: Application round-trip latency	10 ms	5.5 ms	
	KPI#017: Service availability	99.99%	100%	
Aggregated	KPI#03 Downlink Aggregate throughput:	N/A	113 Mbps	OK
	KPI#04 Downlink aggregate throughput:		200 Mbps	
	KPI#017: Service availability		100%	

Based on the final field tests, all measured KPIs met or exceeded the specified requirements, confirming the successful integration and performance of B5G. The results demonstrate low latency, high throughput, and full-service availability across all test cases, ensuring a stable and reliable connection. Users can expect higher-resolution visuals, minimal buffering, and an uninterrupted experience, which is critical for immersive VR sports applications. These trials validate B5G's capability to perform under real-world conditions, meeting the stringent demands of advanced, latency-sensitive services.

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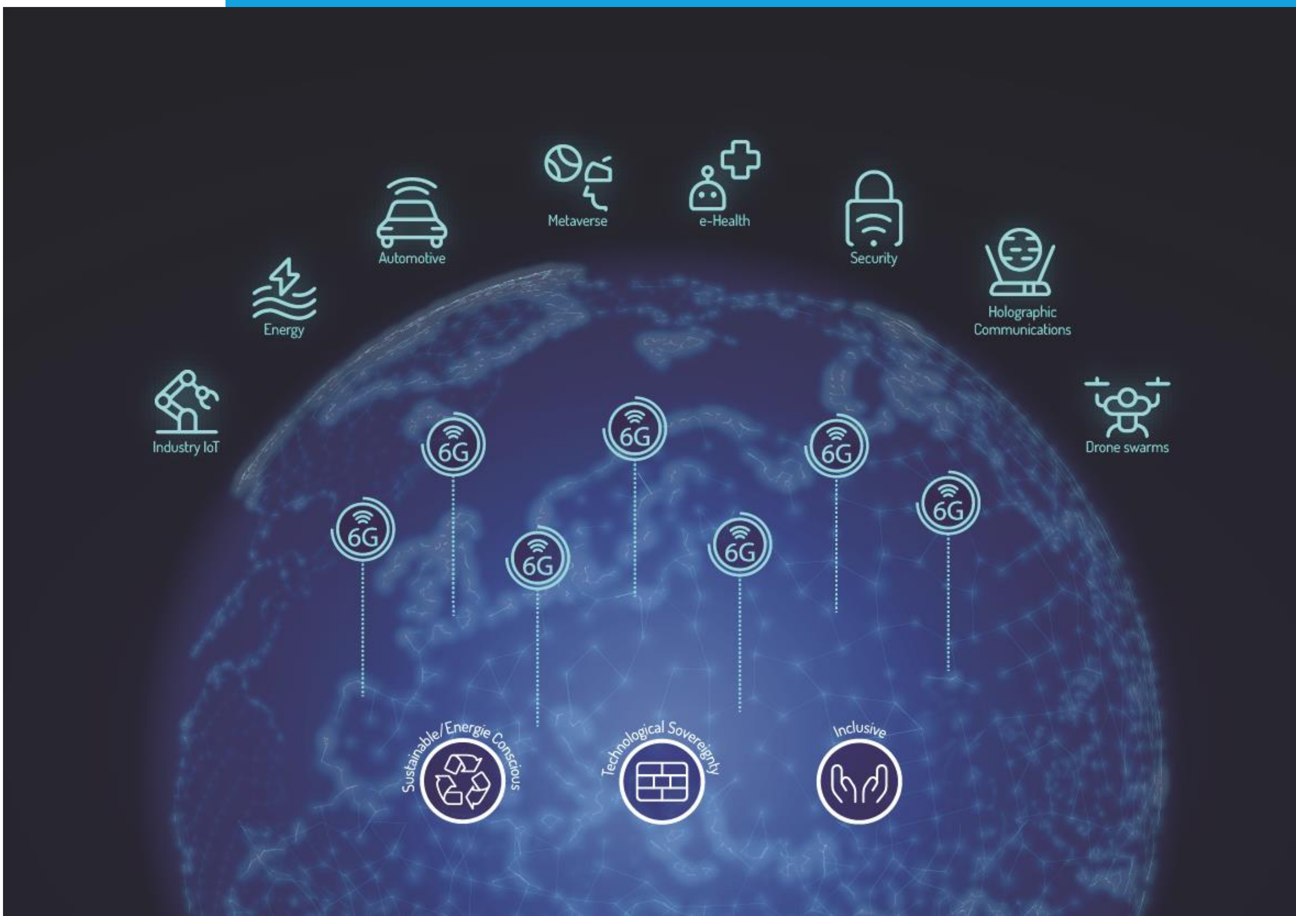

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