Edge IoT Industrial Immersive Technologies and Spatial Computing Continuum

Alliance for IoT and Edge Computing Innovation

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1. Executive Summary

This position paper on edge Internet of Things (IoT) industrial immersive technologies created by the Alliance for IoT and Edge Computing Innovation (AIOTI) aims to provide the vision of the convergence of edge IoT, artificial intelligence (AI), digital twins (DT), immersive triplets (IMT), intelligent mesh connectivity, IoT of senses (IoTS), software-defined automation (SDA) and spatial computing technologies to create an industrial real-digital-virtual continuum. Such continuum is made of immersive environments, which are computer-generated virtual worlds where users can sense as if they were physically embodied in that generated perception context.

The convergence of these technologies into industrial immersive solutions advances the integration and application of edge intelligent immersive technologies combining augmented reality (AR), virtual reality (VR), mixed reality (MR), and extended reality (XR) with concepts like metaverses, omniverse, multiverses, next generation spatial web, Web 4.0 as part of future virtual worlds.

Such convergence of industrial immersive technologies at the edge can improve efficiency, reduce downtime, enhance safety, and better decision-making in industrial settings. However, to be effectively deployed, it both requires a strong interdisciplinary collaboration and presents challenges like robust hardware (HW) design and cost-effective availability, data security and privacy preserving methods, and effective industrial workflow integration. As technology advances, the adoption of such convergence in industry is expected to grow, offering transformative benefits across various sectors and vertical markets, including industrial manufacturing, product operations, design and maintenance, training and collaboration, data visualisation, mobility and logistic, energy, automotive, aerospace, and healthcare.

The EU recognises Web 4.0 as a revolutionary technological shift toward an immersive, seamlessly interconnected world, viewing virtual worlds as a critical transition component [12][13][11]. Swift technological progress in edge IoT, AI, immersive technologies, and enhanced connectivity infrastructure have enabled the feasibility of virtual worlds. These virtual environments are key to the EU Digital Decade targets [16], influencing how individuals live, work, create, and share content and how businesses function, innovate, produce, and engage with consumers.

Edge IoT industrial immersive technologies create or imitate the physical world through digital simulation (Phygital [1]) and virtual sensations giving the user a unique experience of the three-dimensional (3D) spatial computing environment. Phygital is a mix of "physical" and "digital," combining the physical and digital worlds to complete one mixed experience.

Edge spatial computing (ESC) is a novel computing paradigm focusing on understanding and interacting with the physical world in a 3D space close to the source. Spatial computing encompasses the processes and tools for capturing, processing, and interacting with 3D data. These technologies enable human-computer interaction that simulates interactions in real-world physical environments rather than being limited to screens and machines.

ESC enhances the capabilities of autonomous edge IoT devices, robotics, and machines to interact more naturally with humans. It integrates with VR, AR, MR, XR, natural user interface, contextual, affective, and ubiquitous computing in a 3D space, utilising computer, and machine/computer vision to comprehend real-world scenarios.

The topics presented in this AIOTI position paper are aligned with the AIOTI Strategic Research and Innovation Agenda (SRIA) and illustrate the evolution of these topics into convergence ingredients of edge industrial immersive technologies.

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List of Acronyms

3C	Connected Collaborative Computing
3D	Three dimensional
AI	Artificial Intelligence
AIOTI	Alliance for IoT and Edge Computing Innovation
AIOTI SRIA	AIOTI Strategic Research and Innovation Agenda
AoI	Areas of Interest
API	Application Programming Interface
AR	Augmented Reality
BIM	Building information Modelling
CBDC	Central Bank Digital Currency
DAO	Decentralised Autonomous Organisation
dApp	Decentralised app
DeFi	Decentralised finance
DL	Deep Learning
DLT	Distributed Ledger Technologies
DoF	Degrees of Freedom
DT	Digital Twin
E2E	End to End
ESC	Edge Spatial Computing
FoV	Field of View
FPS	Frames per Second
FW	Firmware
HMD	Head-Mounted Display
HMI	Human-Machine Interface
HW	Hardware
IMT	Immersive Triplets
IoT	Internet of Things
IIoT	Industrial Internet of Things
IoT DT	IoT Digital Twin
IoTS	Internet of Things Senses
IT	Information Technology
ITM	Immersive Triplets
JCAS	Joint Communication and Sensing
LoRa	Long Range Radio
LoRaWAN	Long Range Wide Area Network
MEC	Multi-access Edge Computing
ML	Machine Learning
MR	Mixed Reality, Machine Reasoning
NFT	Non-Fungible Token
NLP	Natural Language Processing
NUI	Natural User Interface
PCCR	Pupil Centre Cornea Reflection
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Networks
RF	Radio Frequency
SDK	Software Development Kit
SLAM	Simultaneous Localization And Mapping
SoS	Systems of Systems
SRIA	Strategic Research and Innovation Agenda
SW	Software
UI	User Interface
VR	Virtual Reality
VV&T	Verification, Validation and Testing
Wi-Fi	Wireless Fidelity
XAI	Explainable AI
XR	eXtended Reality

2. Vision and Objectives

Fusion and convergence of technologies sparks innovation, allowing for cross-pollination of ideas, the creation of novel approaches, and transforms industrial landscape by enabling new edge IoT devices, systems, services, and business models. Developing cutting-edge IoT industrial immersive technologies and spatial computing requires a holistic, interdisciplinary approach as a driver of knowledge creation, research, and innovation. Collaboration between the disciplines is thus a vital complement to the grow of the disciplines themselves.

The vision for industrial immersive technologies fusing and converging several technology enablers is to create a highly advanced and interconnected industrial landscape. This landscape leverages the convergence of edge IoT, AI, generative heuristics, Web 4.0, DT, IMT, IoTS, AR, VR, MR, XR, SDA and verse technologies (metaverse, omniverse, multiverse). These concepts represent layers of interconnected virtual spaces. The metaverse refers to a single, universal virtual world. The omniverse is a network of multiple metaverses, potentially operated by different entities but interconnected seamlessly, allowing users to navigate from one to another without leaving the virtual environment. The multiverse extends this idea further into a virtually infinite number of diverse universes within broader narratives.

As a result, these technological developments have the potential to revolutionise industrial processes, training, and collaboration through edge IoT and spatial technologies. These technologies cover the Connected Collaborative Computing (3C) continuum that requires intelligent orchestration, to optimise security and sustainability aspects.

The IoT concept entails two main components: Internet and Things. These represent technologies that are evolving and advancing in their own paths as illustrated in Figure 2-1.

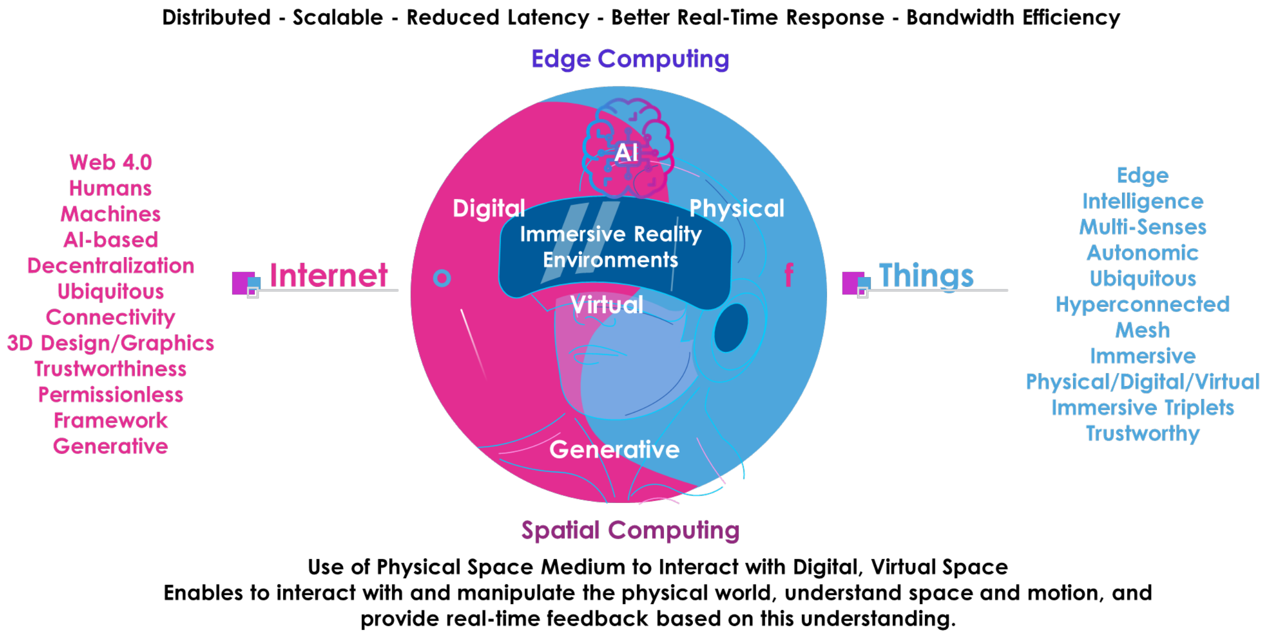

Figure 2-1 IoT - "Internet" and "Things" evolution.

The Internet expands into novel decentralised web paradigms and 3D spatial representation, including holographic representations and immersive technologies. Things are becoming intelligent, mobile, and autonomous, based on self-X features such as self-configuration, self-awareness, and self-diagnostic, using edge AI to process information from multiple sensors and control multiple actuators based on multi-protocol intelligent connectivity, thus enabling devices to adapt to their environments, optimise their performance, and anticipate maintenance needs without human intervention.

The strategic emphasis on IoT and edge computing is progressively moving from platforms to IoT-enabled industrial immersive applications, necessitating packaged, application-centric business solutions to create value. The concept of data gravity in edge IoT industrial immersive technologies and spatial computing pushes the need to process data at the time and place, which offers the most significant business benefit.

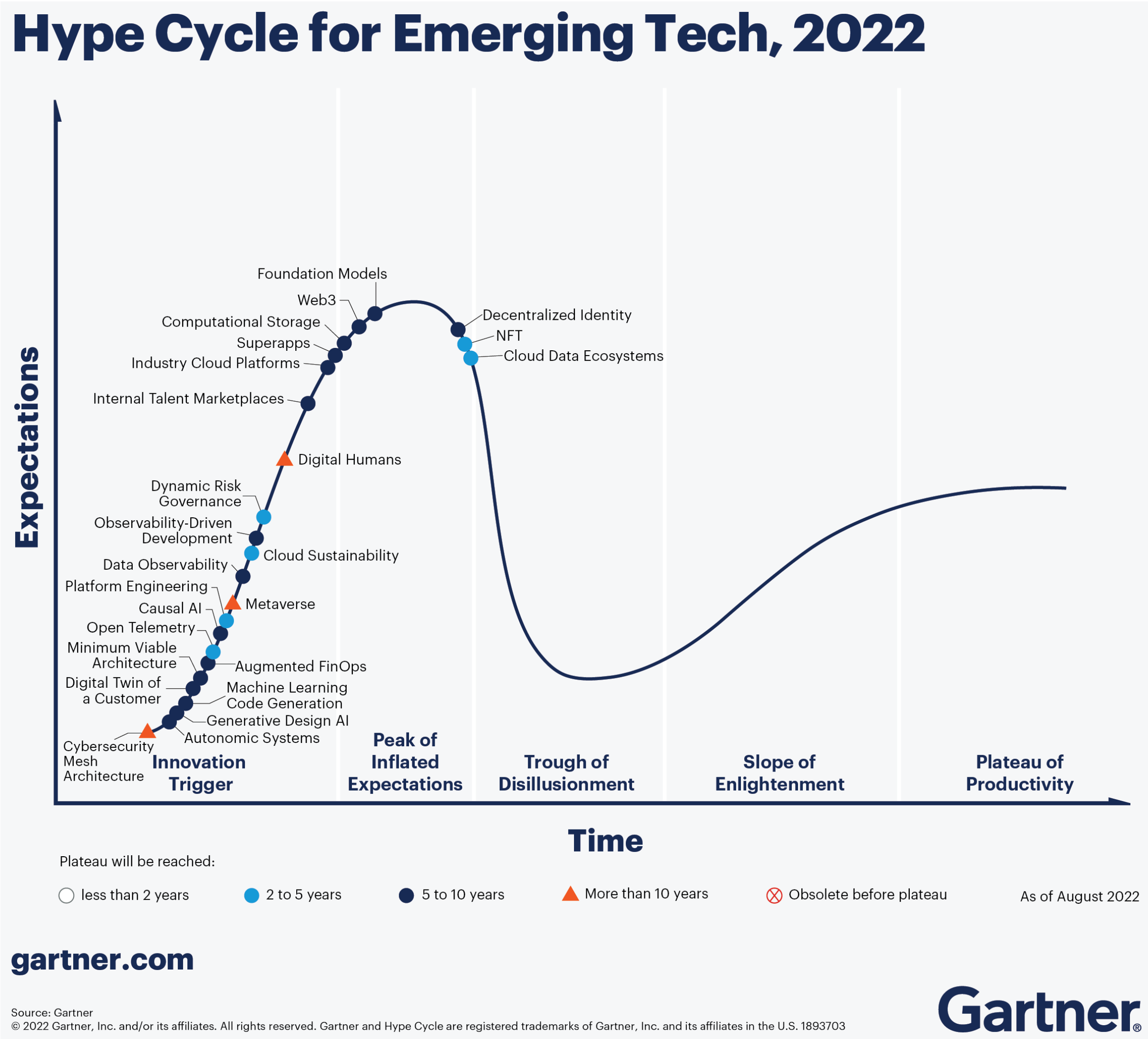

Figure 2-2 Gartner Hype Cycle for emerging technologies 2022. Source: [32]

Gartner predicted that metaverse technology would fully mature in the following years, as illustrated in Figure 2-2, with industrial metaverse indicating the level and potential of technology [53]. The industrial metaverse is the concept of a digital world that mirrors and simulates real machines and factories, buildings and cities, grids, vehicles, and transportation systems [54].

By seamlessly integrating different computing paradigms like cloud, edge, spatial computing, Industrial Internet of Things (IIoT), industrial AI, immersive triplets, and DTs, the industrial metaverse can optimize processes and drive sustainable practices, ultimately shaping the future beyond simulation.

Gartner's emerging technologies [32] focus is on evolving and expanding immersive experiences, accelerating AI automation, and optimising technologist delivery. The evolving technologies include decentralised identity (DCI), which allows entities/users to control their digital identity by leveraging technologies such as blockchain or other distributed ledger technologies (DLTs) and digital wallets; digital humans, which are interactive, AI-driven representations that have some of the characteristics, personality, knowledge, and mindset of a human; metaverse characterised as a persistent collective virtual 3D shared space, created by the convergence of virtually enhanced physical and digital reality, providing enhanced immersive experiences; Non-Fungible Token(NFT) is a unique programmable blockchain-based digital item that publicly proves ownership of digital assets, such as digital art or music, or physical assets that are tokenised; and the Web stack of technologies for developing decentralized web applications that enable users to control their own identities and data.

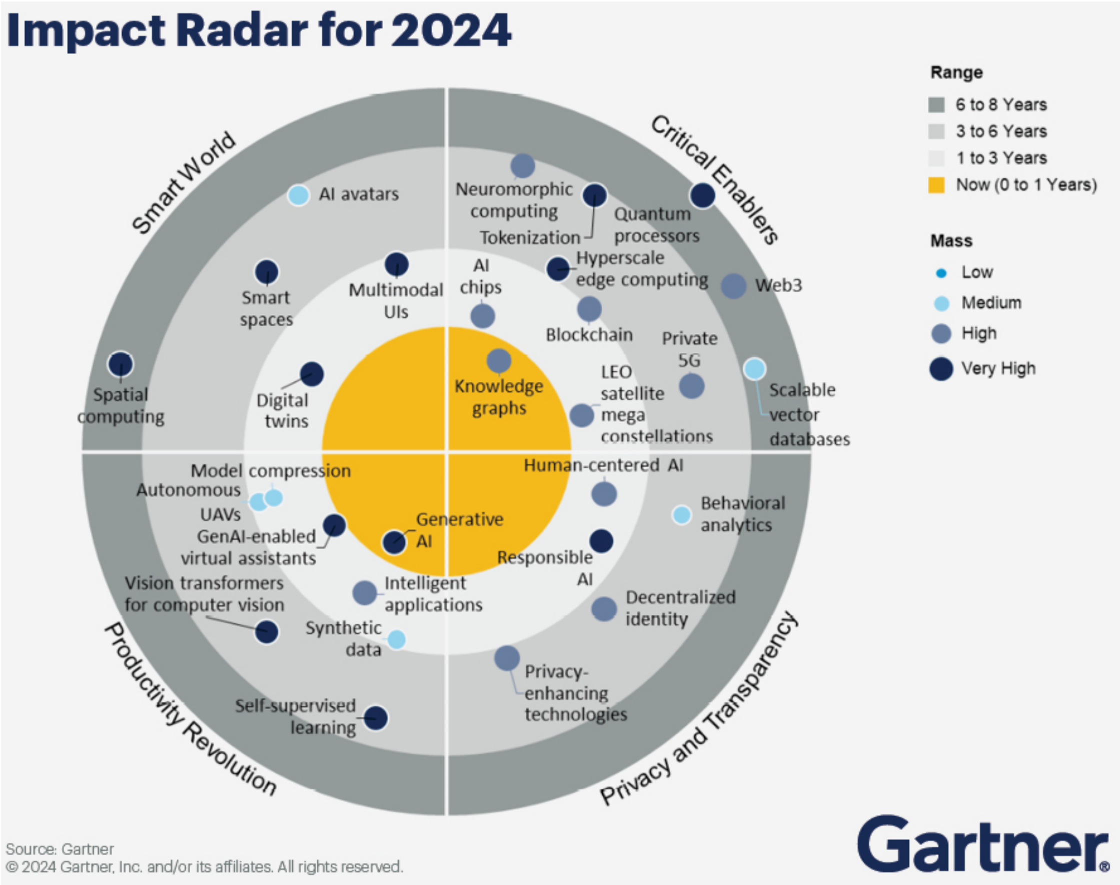

Figure 2-3 Gartner impact radar for 2024. Source: [31].

One of the key themes in the Gartner Emerging Tech Impact Radar [31] illustrated in Figure 2-3 is the intelligent world, which covers changes in how people and machines interact with people, places, content, and things based on the convergence of online and offline experiences. In this context, some key edge IoT industrial immersive technologies enablers are highlighted.

Concepts such as AI avatars representing human-like virtual personas created using computer-generated imagery and various AI techniques and applications; DTs reflecting the technology-enabled proxies that generate a digital representation by mirroring the state of a single or collection of physical or virtual assets, processes, persons or organisations; multimodal user interfaces (UIs) referring to models in which user and machine interactions can co-occur; smart spaces represented by physical environments in which humans and technology-enabled systems interact in increasingly open, connected, coordinated and intelligent ecosystems; and spatial computing defined as a computing environment that combines physical and digital objects in a shared frame of reference.

These enablers are accelerating the overall convergence and fusion of technologies to support the scale and complexity of interactions in immersive applications, enabling the creation and maintenance of new user experiences, predicting and monitoring user behaviour, data processing, and fully autonomous operation of complex industrial immersive triplets and DTs.

Immersive technologies have started to be used in different industries with automotive industry, providing outstanding services and making high-quality, eco-friendly products. These technologies are shaping the future of autonomous driving by defining new ways of interacting with SDA and software-defined vehicles (SDVs). SDA is a paradigm shift in automation development focusing on leveraging software (SW) methodologies and tools to drive the automation process, while SDVs are the next evolution of the automotive industry, with the vehicle managing its operations, adding functionality, and enabling new features primarily or entirely through SW. The SDA combined with SDV reflects the gradual transformation of vehicles towards intelligent, connected, autonomous computing units on wheels that can be continuously upgraded. Edge IoT industrial immersive technologies and spatial computing are part of this development, and immersive solutions in automotive cockpits, AR and holographic displays, gesture recognition, and voice control create a more interactive and intuitive driving experience.

The next-generation IoT technologies significantly evolve from the traditional concept of interconnected devices. This new era is characterised by an advanced ecosystem where the "Internet" evolves into a more decentralised, secure, and user-centric Web 4.0, and the "Things" become increasingly intelligent and autonomous through advancements in AI and edge computing. Incorporating immersive technologies, spatial computing, and holographic representations, this next-generation IoT offers transformative possibilities for various industrial sectors. This shift demands a new equilibrium between edge and cloud capabilities, ensuring a holistic view of data processed at the edge considering contextualisation, which implies the understanding of complex situations by aggregating information, applying AI patterns, and incorporating user behaviour. Putting any decision support into a local, global context and somehow visualising events with their context, abstracting complex situations and adding graphical animations of actual and future scenarios is essential.

Decentralised Networks and Web 4.0: The transition from a centralised Internet architecture to a decentralised Web 4.0 framework is foundational to the next-generation IoT. Web 4.0 utilises blockchain technology to create a more secure, transparent, and user-controlled online environment. In the context of IoT, this means devices can communicate and transact in a peer-to-peer manner without centralised intermediaries. This decentralisation enhances security, reduces the risk of single points of failure, and enables new forms of device interoperability and data sharing.

Intelligent and Autonomous "Things": Next-generation IoT devices are not just hyperconnected but more intelligent and equipped with AI and machine learning (ML) capabilities. These devices can process data, make decisions, and act autonomously. Edge computing plays a crucial role here, allowing data processing to occur closer to where data is generated, thereby reducing latency, conserving bandwidth, and enhancing privacy. The devices are equipped with self-X capabilities (e.g., self-configuration, self-awareness, and self-diagnosis) that enable them to adapt to various environments, optimise their performance, and anticipate maintenance needs without human intervention.

Immersive Technologies and Spatial Computing: Immersive technologies, including AR, VR, and MR, known collectively as XR, combined with spatial computing, bring a new dimension to IoT. These technologies allow users to interact with digital information and IoT devices more naturally and intuitively. For instance, engineers could use AR/MR glasses to see a holographic overlay of the internal component of a machine, sourced from real-time IoT sensor data, facilitating quicker diagnostics and cheaper repairs.

Holographic Representations: Holographic technology is set to revolutionise how we visualise and interact with data. In an IoT context, holographic representations can provide detailed, three-dimensional visualisations of data and systems.

This can be particularly useful for complex industrial processes, urban planning, and healthcare diagnostics, offering a level of detail and interactivity that traditional screens cannot match, however, paying in terms of quality of the user's field of view.

Multi-Protocol Intelligent Connectivity: The need for advanced connectivity solutions grows as IoT devices become more sophisticated. Next-generation IoT technologies will likely employ intelligent connectivity systems that can dynamically choose the best communication protocol (e.g., Wi-Fi, 5G/6G, Bluetooth, LoRaWAN) based on the specific requirements of each task, such as quality of service (QoS), price, bandwidth, latency, range, and power consumption. This flexibility ensures that devices communicate efficiently and reliably in various environments, scenarios and use cases.

The next-generation IoT represents a convergence of several cutting-edge technologies, each contributing to a more intelligent, interactive, and interconnected world. By combining the decentralised principles of Web 4.0 with the intelligence and autonomy of advanced IoT devices and enhancing user interaction through immersive and holographic technologies, this new era of IoT is set to offer unprecedented opportunities for innovation and transformation across all aspects of society. As these technologies evolve and mature, the potential applications and impacts of next-generation IoT will only expand, promising a future where digital and physical realms are more closely integrated and industrial immersive technologies create distinct experiences by merging the physical world with the digital and virtual realities as illustrated in Figure 2-4.

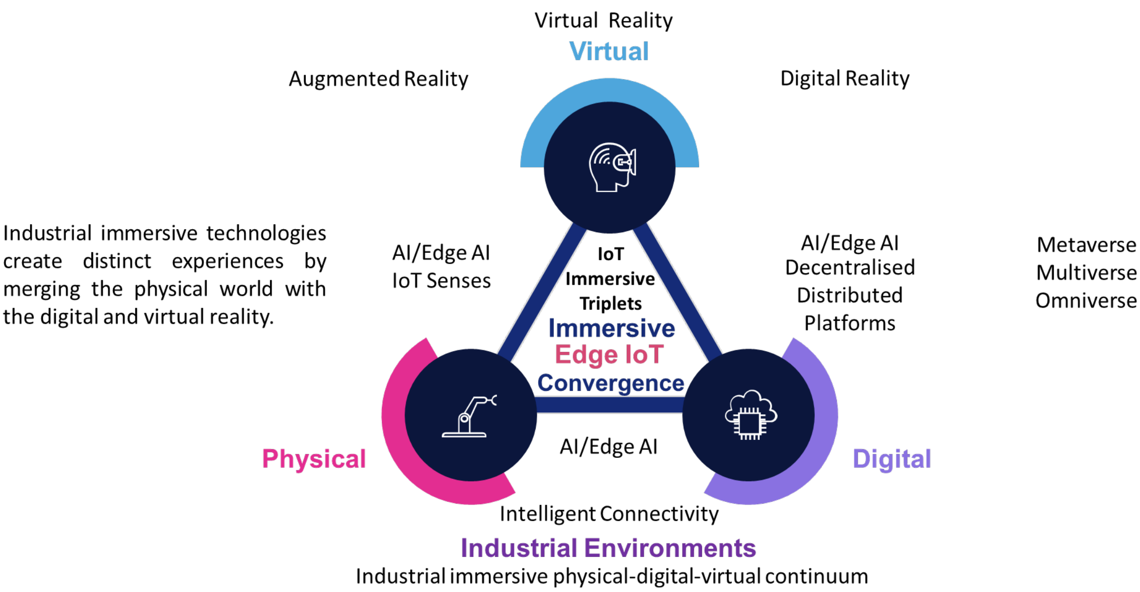

Figure 2-4 Edge IoT industrial immersive technologies.

The future vision of industrial immersive systems (VR, AR, MR verses - metaverse, omniverse, multiverse) converging with IoT, edge computing, AI, spatial computing, and Web 4.0 represents a transformative leap towards creating interconnected, intelligent, and highly immersive industrial environments and brings new important feature developments as presented below.

Seamless Integration of the Physical, Digital, Virtual and Cyber Worlds: In this vision, industrial environments are augmented with spatial computing and immersive technologies, allowing for a seamless fusion of tangible, digital, virtual, and cyber realms. Workers equipped with AR glasses or VR headsets can visualise IoT sensor data overlaid directly onto machinery, see real-time AI-driven analytics, and interact with 3D models of complex systems. This integration enhances understanding, speeds up decision-making, and facilitates remote collaboration with experts worldwide, breaking geographical, location and spatial barriers to build "virtual worlds" technologies and applications.

Autonomous and Self-Optimising Factories: By leveraging IoT, edge computing, and AI, factories become fully autonomous and capable of self-optimisation in real-time. Machines with sensors continuously feed data to edge computing devices that analyse this information locally, minimising latency. AI algorithms predict maintenance needs, optimise production schedules based on real-time demand, and automatically adjust processes to reduce waste and energy consumption. This creates a highly efficient, sustainable manufacturing environment that can quickly adjust to evolving market conditions.

Personalised and Adaptive Workspaces: Every worker's experience is personalised in these future industrial settings. AI understands individual preferences, skill levels, and work styles, adjusting the information displayed through immersive interfaces accordingly. This personalisation extends to learning and training, where immersive simulations adapt in real-time to the learner's progress, offering a tailored educational experience that maximises skill acquisition and retention.

Decentralised Manufacturing Ecosystems: With the integration of Web 4.0 technologies, manufacturing ecosystems become decentralised and more democratic. Blockchain enables secure, transparent supply chain operations, smart contracts automate transactions, and decentralised finance (DeFi) solutions offer new financing models for manufacturers. This shift increases efficiency and transparency and opens the manufacturing ecosystem to smaller players, fostering innovation and collaboration.

Immersive Triplets, Avatars and Spatial Computing: Immersive triplets, spatial virtual replicas of physical systems, become fully immersive, allowing engineers to interact with and analyse complex systems in a 3D space. Spatial computing enables these immersive triplets to be spatially mapped to their physical counterparts, offering an intuitive and comprehensive understanding of how digital, virtual, and cyber changes affect the physical world. This capability is crucial for testing new ideas, predicting system behaviours under various conditions, and training AI models with virtual data, reducing the need for costly physical prototypes.

Enhanced Human-Machine Interaction: The convergence of these technologies revolutionises human-machine interaction. A set of AI-related technologies, like natural language processing (NLP), ML, deep learning (DL), and generative AI enable intuitive and context-aware voice and gesture controls. Workers communicate with machines as easily as they would with human colleagues, issuing commands, receiving feedback, and even collaborating on tasks. Avatars can support advanced and natural conversation with immersive technology users, protecting the feeling of immersion. This enhances safety, efficiency, and the overall user experience in industrial environments.

Enhanced Human Expression: The availability of systems that provide rich feedback to humans across multiple sensory modalities, including immersive triplets, enables users to express precise actions relating to objects. Such actions can indicate relative positions, orientations, and applied force related to digital constructs or virtual replicas of real-life objects. This considerably enhances the efficiency and precision with which humans can express themselves intuitively. This capability creates a new way for people to work.

Global, Real-Time Collaboration Platforms: Immersive systems and Web 4.0 technologies facilitate the creation of global, real-time collaboration platforms. Teams globally can work together in a shared virtual space as if they were in the same room, accessing shared blockchain assets and leveraging collective intelligence to solve complex problems. This accelerates innovation and fosters a more inclusive and diverse industrial ecosystem.

The vision for the future of industrial immersive systems, intertwined with IoT, edge computing, AI, spatial computing, and Web 4.0, coats a picture of highly efficient, sustainable, and democratised industrial environments.

This future is characterised by intuitive human-machine interfaces, personalised experiences, and a seamless blend of physical and digital worlds, offering vast potential for innovation, collaboration, and growth across all industry sectors. While challenges remain in realising this vision, the potential benefits make it a compelling direction for the future of various industrial domains.

Edge IoT industrial immersive technologies play crucial roles in facilitating a sustainable twin digital and green transition. This synergy not only accelerates digital transformation but also enhances the sustainability of processes, environments, and ecosystems.

The convergence of edge IoT, AI, generative heuristics, Web 4.0, DT, IT, IoTS, AR, VR, MR, XR, verse technologies (metaverse, omniverse, multiverse) and system design integrated approach drives efficiency and sustainability. It ensures that digital technology advancements directly contribute to greener outcomes, aligning technological progress with environmental stewardship. The twin digital and green transition is, thus, seen not merely as a parallel development of digital and sustainable practices but as their convergence towards a holistic goal.

3. Definitions and Taxonomy

IoT and edge computing research and innovation address IoT/edge continuum distributed architectures, intelligent connectivity. End-to-end (E2E) security, heterogenous IoT edge mesh, IoT DTs, AI, IoT swarm systems, IoTS, trustworthiness, verification, validation, and testing (VV&T), standardisation, and the convergence of all the above into the Internet of Intelligent Things.

Immersive technology refers to any technology that blurs the line between the physical and digital worlds, creating a sense of presence and engagement for the user. Immersive technologies aim to transport users to virtual environments or enhance their real-world experiences by overlaying digital information onto their physical surroundings through real-time interactions in physical, digital, virtual, cyber, and spatial environments.

Immersive technologies have emerged as a revolutionary approach to creating digital experiences that feel real to users.

By incorporating various tools and systems, immersive technology encompasses real-time interactions in physical, digital, virtual, cyber, and spatial environments using a broad spectrum of experiences that blur the boundaries between the physical and digital worlds, providing innovative ways to interact, explore, and learn.

IoT and edge computing enable innovation and broad adoption in immersive technologies and applications by bringing the novel elements of converging technologies to the edge and real-time interaction between the physical and virtual worlds. An overview of edge immersive technologies is illustrated in Figure 3-1.

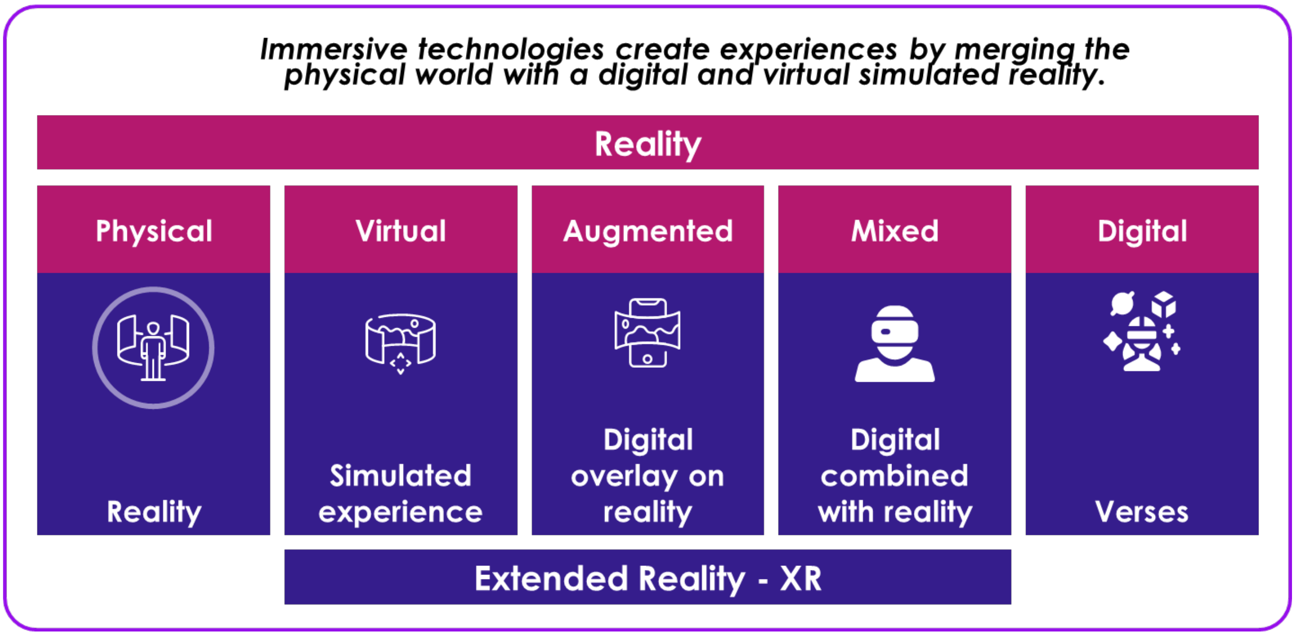

Figure 3-1 Edge IoT immersive technologies.

The IoT devices, mobile computing units, and fleets of these interconnected devices are evolving, and the amount of information generated and exchanged by these devices grow significantly at the network edge.

Consequently, the constraints due to extremely high latency and network bandwidth usage will limit the transfer of these massive volumes of data to the cloud. Using AI processing capabilities at the network edge can unleash the potential of data generated by sensors and devices.

2.1 Virtual reality

VR is a computer-generated simulation of an environment using 3D computer modelling, which immerses users in a wholly digital environment, often using a head-mounted display and hand controllers to simulate the physical presence in the virtual world.

The immersion is achieved through hand-held controllers or gloves fitted with sensors, VR headsets or head-mounted displays (HMDs) that cover the user's field of vision, delivering content that responds to the user's movements and translate them into actions to simulate the physical presence in the virtual world, thus allowing users to interact in those worlds.

VR involves components and characteristics like immersive experiences that provide a sense of immersion in a computer-generated environment distinct from the physical environment.

The immersion in the virtual world happens by making use of multiple senses, including vision, hearing, and sometimes touch (through haptic feedback), to enhance the realism of the virtual environment by using IoTS devices. Advanced VR systems may also include olfactory (smell) and gustatory (taste) elements to deepen the immersive experience further.

The integration of 3D graphics and environments into virtual spaces is achieved by making use of 3D computer modelling, one of the most interesting types of graphic design, and is designed to be interactive and responsive to the user's actions. This requires substantial computing power to maintain real-time rendering and interaction. An interesting offering in this domain is the open-source library for easy 3D data processing, ML and visualisation and called Open3D [45].

Standards related to VR (see Table I-1) provide guidelines on system design, user interaction, content creation, and health and safety considerations to ensure a high-quality user experience, promoting interoperability between different VR devices and software, and addressing potential health impacts associated with prolonged VR use.

2.2 Augmented Reality

IoT, edge computing and AR are technologies that are changing how we interact with the world. AR combines real-world views with computer-generated elements to create an immersive experience. IoT and edge computing bring the interactions with the physical world, data collection, data storage and processing closer to the network's edge, making AR more accessible, cost-effective, and secure.

AR blends digital content with the real world, allowing users to see and interact with virtual objects or information overlaid onto their physical surroundings through edge IoT devices screens, headsets, and smart glasses.

AR can be defined as an interactive experience of a real-world environment where the objects that reside in the real world are enhanced by computer-generated perceptual information, across multiple sensory modalities, including visual, auditory, haptic, somatosensory, and olfactory. The technical aspects of AR involve integrating digital information with the user's environment in real-time. Unlike VR, which creates an artificial environment, AR uses the existing environment and overlays new information on top of it, creating an actual "augmentation" of the sensed reality. AR can be experienced through various devices, including smartphones, tablets, AR glasses, and HMD creating Phygital mixed experiences.

From a scientific and technical standpoint, AR systems are designed to combine real and virtual worlds, interact in real-time and align virtual and real objects.

The key components of AR systems include sensors and cameras to capture real-world inputs, processing to interpret the sensor input, detect features of the real world, and determine the location and orientation of a device within it, projection systems to display virtual images, display devices to present the integrated digital information to the user. This can include screens, optical projection systems, or touchscreens, enabling users to see and interact with the augmented virtual objects.

Standards related to AR (see Table I-1) aim to harmonize the technical criteria, ensure interoperability between different AR devices and SW, and enhance the user experience by setting benchmarks for performance, safety, and privacy.

AR systems typically consist of several key components such as a perception sensor, e.g., a camera that captures the real-world environment and feeds it into the AR system, a processor to perform image processing on the input of the camera to identify and track features in the real world, a display that presents the digital content and information superimposed on the real-world view (e.g., smartphone screen, a HMD, a projected image), tracking and alignment to align virtual content with the real-world environment (e.g., marker-based tracking, feature-based tracking, or simultaneous localisation and mapping- simultaneous localization and mapping (SLAM)), interaction that allows users to interact with virtual content (e.g., via gestures, voice commands, or a handheld controller), SW that includes the programming that makes the AR experience implemented using various AR SW development kits (SDKs).

With edge computing, the processing required for AR applications can run on edge devices rather than relying on cloud computing and remote servers. This significantly reduces cloud-based latency of AR systems and data transmission costs. As a result, IoT and edge computing make AR more accessible and improves the overall user experience. AR applications that run at the edge are also less susceptible to the cyber threats faced by cloud-based AR applications (which are much more vulnerable to hacking and data theft). This is because edge computing keeps data local, making it far less susceptible to attacks, as data isn't required to travel to remote cloud servers and back. IoT and edge computing enables AR experiences in real-time, which positively impacts live sports broadcasting, translation, and product visualisation.

AR and VR are different technologies with specific uses and applications. The differences between AR and VR are as follows: AR enhances the real world by superimposing computer-generated elements, while VR creates an entirely artificial environment that replaces the real world.

AR is interactive and allows users to view and interact with their real-world surroundings, while VR is designed to immerse users in a wholly digital environment. AR systems typically use a camera to capture the real world and display digital content superimposed on it. VR systems usually use head-mounted displays to fully immerse users in digital content. The immersion level of VR apps is greater than AR and has been proven beneficial for training purposes. The key differences between AR and VR lie in their relationship to the real and digital worlds. AR enhances the real world with computer-generated elements, while VR completely replaces it with a digital environment.

Knowing the difference between AR and VR is important for understanding their potential uses and limitations and the different roles Edge computing plays for each technology. It also helps to better understand the impacts of these technologies in different industrial sectors and across these sectors.

2.3 Mixed reality

MR refers to blending physical and digital worlds to produce new environments and visualisations where physical and digital objects coexist and interact in real-time. MR encompasses a wide range, from AR, where real-world environments are augmented with virtual objects, to VR, where virtual environments incorporate elements from the real world and users are immersed in a simulated digital environment or a digital replica of reality. This continuum highlights the fluidity between the purely physical and virtual worlds, with MR as an intermediary state that integrates both aspects. The level of augmentation can vary from a simple information display to the addition of virtual objects and even complete augmentation of the real world. MR includes all variants where virtual and real environments are mixed and variants where real objects are included in the virtual world.

MR combines elements of VR and AR, allowing users to cooperate with virtual objects anchored to the real-world and interacting with it. MR involves wearing a headset that overlays digital content onto the user's environment while maintaining awareness of the physical world. MR, when integrated with IoT, edge computing, and AI, can significantly enhance immersive experiences across various domains, from industrial applications to everyday consumer use. The concepts of VR, AR, MR immersive technologies are illustrated in Figure 3-2.

Technical and scientific aspects of MR involve seamless integration by the seamless blend of real and virtual worlds, requiring sophisticated sensing, processing, and display technologies, real-time interactions with both real and virtual elements occur in real-time, demanding high computational efficiency and responsive input/output systems, spatial registration by aligning virtual objects with the real world to maintain the illusion of coexistence, necessitating advanced computer vision, sensor fusion, and tracking technologies.

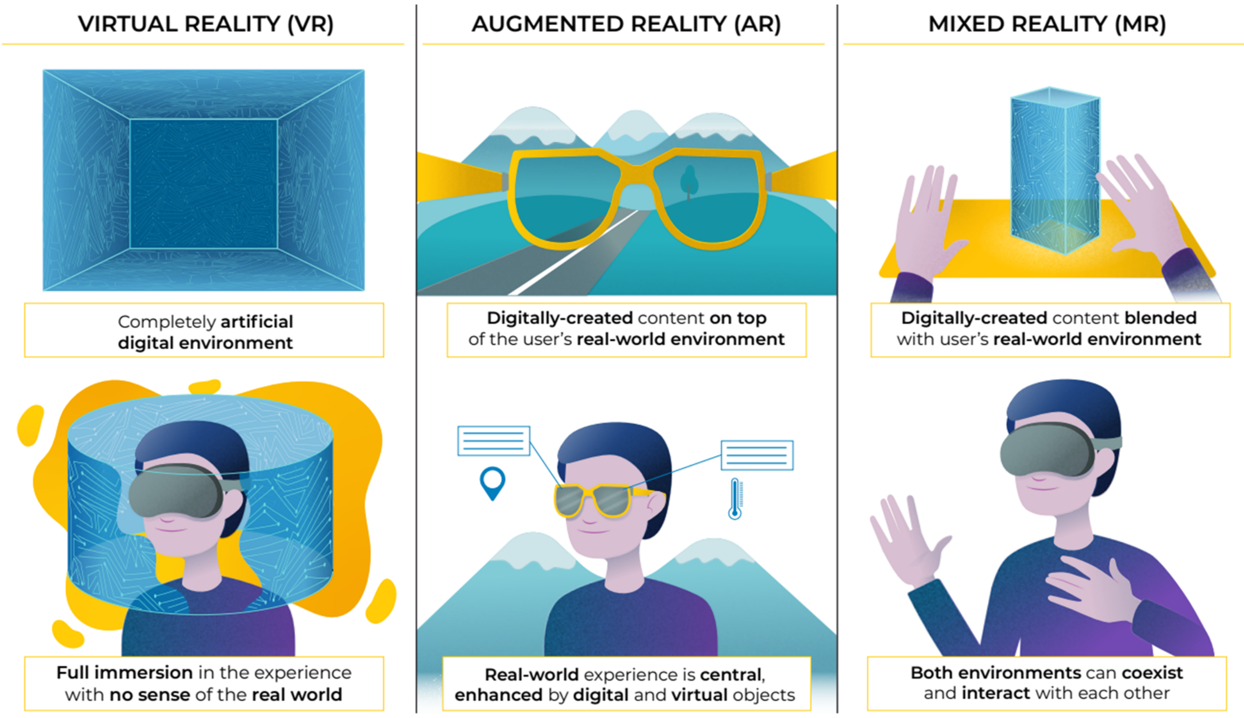

Figure 3-2 Illustration of the concepts of various immersive technologies – VR, AR, MR. Source: [7]

To propose a comparison, differently from MR, original AR applications were dependent on the sensing systems and their external references (like markers) to enable spatial computing. These solutions were effective (e.g., AR platforms) but could not interact with the environment outside the marker except when complex structured solutions were used. Sensor-fusion solutions nowadays overcome those limitations, and the two terms are often swapped in a common language.

Key components and technologies used in MR systems include advanced displays, such as HMDs or smart glasses, which can overlay virtual content onto the physical world, environmental sensing using cameras, depth sensors, and other technologies to capture detailed information about the surrounding environment, spatial computing enabling devices to understand and interact with the physical space around them, including object recognition and spatial mapping, haptic feedback providing tactile feedback to enhance the sense of physical interaction with virtual objects.

Standards related to MR (see Table I-1) aim to provide a framework for terminology, system design, user experience, and interoperability among MR devices and applications to ensure compatibility, safety, and privacy across the diverse ecosystem of MR technology and applications.

In VR, users are immersed in a simulated digital environment or a digital replica of reality. In AR digital information is overlaid on images of reality viewed through a device. The level of augmentation can vary from a simple information display to the addition of virtual objects and even complete augmentation of the real world. However, MR includes all variants where virtual and real environments are mixed and variants where real objects are included in the virtual world.

Edge devices support MR and have new sensors that enable the virtual avatar to maintain eye contact and replicate the facial emotions of actual people. With further advancement in the technology, avatars will be able to express human emotions better and employ body language, giving the impression of a real dialogue in virtual environments.

2.4 Extended reality

XR is an umbrella term that covers immersive technologies ranging from VR to MR, and AR. The combination of intelligent wireless and cellular connectivity and XR technologies enables new mobile experiences for consumers and industrial users and opens a broad range of business opportunities for service.

XR is a term that encompasses the entire spectrum of real and virtual combined environments and human-machine interactions generated by computer technology and wearables. XR technology aims to blend the digital and physical worlds in a seamless and immersive way, leveraging the strengths of VR, AR, and MR to create experiences that could range from entirely synthetic environments (VR) to real-world settings augmented with digital overlays (AR) and environments where physical and digital objects coexist and interact in real-time (MR).

The future technological landscape is profoundly reshaped by the convergence of IoT, edge computing, AI, and industrial immersive technologies such as XR, all within the framework of emerging Internet Web 4.0 technologies. This convergence is expected to bring about a new digital interaction and automation era across various industries and aspects of daily life.

Key aspects and objectives of XR include immersive experiences that could either augment the real world with digital content (AR), blend the real and virtual worlds (MR), or create a fully immersive virtual environment (VR), interactivity across the spectrum of XR by interacting with digital objects overlaid onto the real world or navigating and manipulating an entirely virtual space, multi-sensory engagement using multiple senses, not just sight and sound but potentially touch (through haptic feedback) and other senses

The aim of XR is to create more immersive and compelling experiences, real-time processing of complex data, including spatial mapping, object recognition, and seamless integration of virtual and real elements and the use of wearable and non-wearable edge IoT devices through a variety of HMDs (for VR and MR), smart glasses (for AR), mobile devices, and even future technologies that may provide more unobtrusive ways to blend digital and physical experiences.

Standards and guidelines for XR (see Table I-1) are focused on ensuring interoperability between devices, defining consistent user experience metrics, and addressing ethical considerations and privacy concerns to facilitate the widespread adoption of XR technologies by providing a solid framework for developers, manufacturers, and content creators to follow.

XR streaming enables data-intensive AR and VR applications to be collected in real-time by mobile devices. This opens new fields of application for immersive technologies in the IoT environment.

The elements specific to the immersive technologies represented by XR are Field of View (FoV), which defines an observable area or the range of vision (e.g., 200m) an individual can see via an XR device such as HMD when the user is static within a given XR environment; Degrees of Freedom (6DoF), which describes the position and orientation of an object in space by three components of translation and three components of rotation (e.g., swivels left and right - yawing, tilts forward and backwards - pitching, pivots side to side - rolling). A six degrees of freedom (6DoF) experience allows for moving up and down (elevating/heaving - Y Translation), moving left and right (strafing/swaying - X Translation), moving forward and backwards (walking/surging - Z Translation) in addition to yawing, pitching, and rolling. Haptics are mechanisms and technologies for tactile feedback to enhance the interaction experience with onscreen interfaces via touch, vibration, and force feedback, creating a virtual sense of touch. HMDs are used as devices with miniature displays or projection technology integrated and mounted on helmets/hats or into eyeglasses to create a virtual sense of sight and sound. Positional tracking using 6DoF allows edge devices to estimate their position relative to the environment by combining HW and SW to detect the absolute position. Head tracking refers to the movement of the user's head and is used to move the images displayed to match the head's position. Orientation tracking uses accelerometers, gyroscopes, and magnetometers to determine how the user's head turns. Eye tracking facilitates and seizes the way the user's eyes are looking using light from infrared cameras, which is directed toward the participant's pupils, inducing reflections in both the pupil and the cornea. These centre corneal reflections (PCCR), can provide information about the movement and direction of the eyes. Eye tracking is utilised to capture and analyse visual attention using heatmaps, gaze replays, and output metrics for areas of interest (AoI), considering the time to first fixation and time spent. Full body tracking is defined as the procedure of tracing humanlike movements of the virtual subject within the immersive environments by recording in real-time via HMDs and multiple motion controller peripherals, the scene location coordinates of moving objects to catch the movement of the entire body of the user. Inside-out tracking refers to the positional tracking technique commonly used in XR technologies to track the position of HMDs and motion controller accessories. The difference compared with outside-in tracking is the camera location or other sensors used to determine the object's position in space. The XR edge devices use an inside-out tracking watch to determine how its position changes about the environment. Outside-in tracking refers to positional tracking, where fixed external sensors are placed around the viewer to decide the headset's position and associated tracked peripherals [7].

A summary of existing typical XR key performance indicators (KPIs) is presented in **Table *3-1***. AR can be considered a simple version of MR, and advanced AR technologies may be merged into MR, while ultimate XR may only consist of MR and VR.

Table 3-1 Typical existing VR, AR, and MR system specifications and technical requirements [21].

Specification	VR	AR	MR
Screen	Occlusion	Translucent	Translucent
Display	HMD	OHMD	OHMD
Environment	Virtual	Passive virtual & real	Passive virtual, active virtual, real
Uplink Data Rate	150 kbps	0.02 - 1.0 Gbps	0.02 - 1.0 Gbps
Downlink Data Rate	0.02 - 1.0 Gbps	0.02 - 1.0 Gbps	0.02 - 1.0 Gbps
Latency	20 - 1000 ms	20 ms	10 ms
Refresh Rate	~90 Hz	~90 Hz	~90 Hz
Pixels-per- Degree	10 - 15	30 - 60	30 - 60
Field-of- View	100°- 150°	20° - 50°	20° - 50°

The progression towards Web 4.0 involves the Internet becoming more intelligent and autonomous. Technologies like the semantic Web enhance data connectivity through better-structured, linked data that machines can understand and process. In an XR context, this means dynamically generated content that is contextually relevant to what the user sees or interacts with. Blockchain technologies ensure secure, decentralised processing and storage of the massive amounts of data generated by edge IoT devices and used in XR environments.

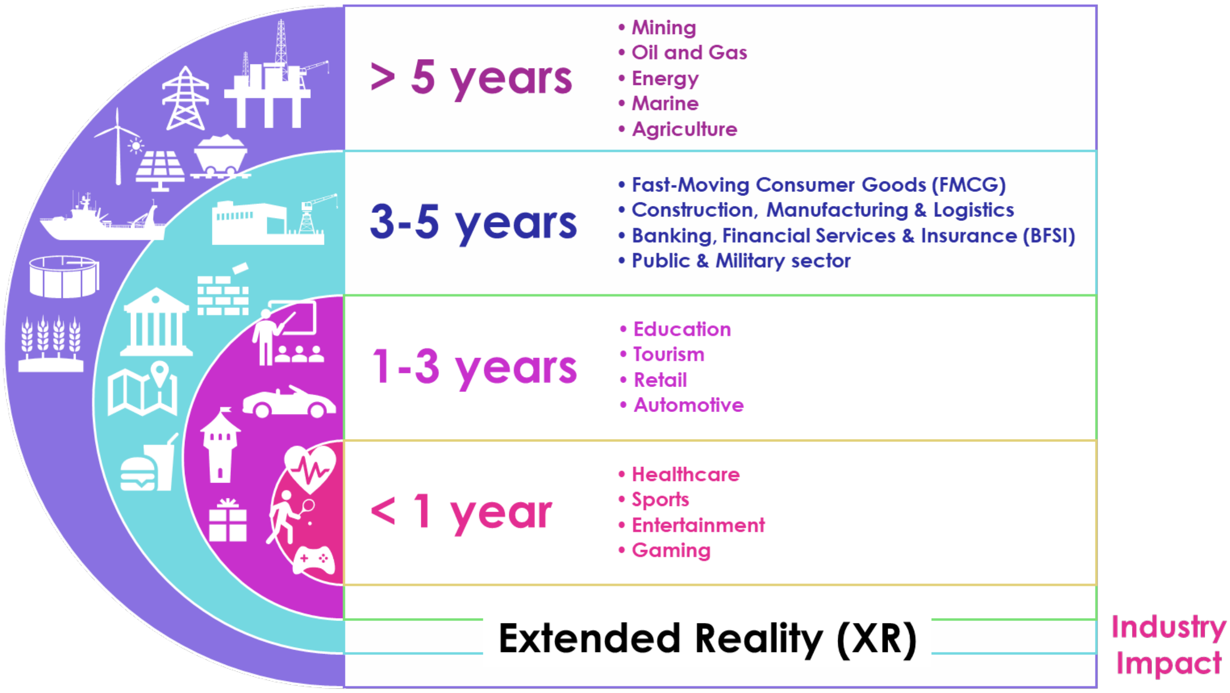

Figure 3-3 XR application landscape. Source: Adapted from Frost & Sullivan

The convergence of IoT, edge computing, AI, and XR within the Internet Web 4.0 framework is poised to create a more connected, responsive, and immersive digital future. This will enhance current applications and open new possibilities in how humans live, machines operate, work, and interact with humans and other machines in physical, digital, virtual, and cyber environments. Figure 3-3 illustrates the expected application landscape for XR immersive technology.

2.5 Metaverse

The terms "verse," "metaverse," "omniverse," and "multiverse" are part of the future development of immersive technologies, and each term represents a concept, ranging from digital, virtual, and cyber ecosystems about the universe. "Verse" is a general suffix that denotes a type of universe and is used as a shorthand in various contexts to refer to a universe or a particular immersive environment within a broader context.

Verses are dynamic concepts in digital technology that offer immersive digital experiences that seamlessly interconnect people, places, machines, objects, and information in real-time, transcending the constraints of the physical world.

The metaverse displays six characteristics as illustrated in Figure 3-4: **immersiveness**, which refers to a computer-generated virtual environment sufficiently realistic for users to feel psychologically and emotionally involved and through sensory perception (e.g., sight, sound, touch, temperature, and pressure) and expressions (e.g., gestures and signs), it is possible to understand it; **spatiotemporal** that represents the limits to the real world due to the finiteness of space and the irreversibility of time, which refers to the break of space and time limitations in the metaverse, a virtual space-time continuum parallel to the real one; **sustainability** representing a high degree of independence and a closed economic cycle indicates that the metaverse maintains a consistent value system and a closed economic loop; **interoperability** that implies that users can seamlessly move between virtual worlds (i.e., sub-verses) without interrupting the immersive experience, considering that the digital assets used for rendering or reconstructing virtual worlds can be interchanged between different platforms; **scalability**, which is the ability to remain efficient with the number of concurrent users/avatars, the level of scene complexity, scope, and range of interactions between users/avatars and **heterogeneity**, considering the existence of heterogeneous virtual spaces with distinct implementations, heterogeneous physical devices with different interfaces, heterogeneous data types, heterogeneous communications modes, and diverse human psychology. Avatars can seamlessly traverse various virtual worlds, including sub-verses, to experience a digital environment and participate in virtual economic activities through physical infrastructures and a metaverse incentive [8][61].

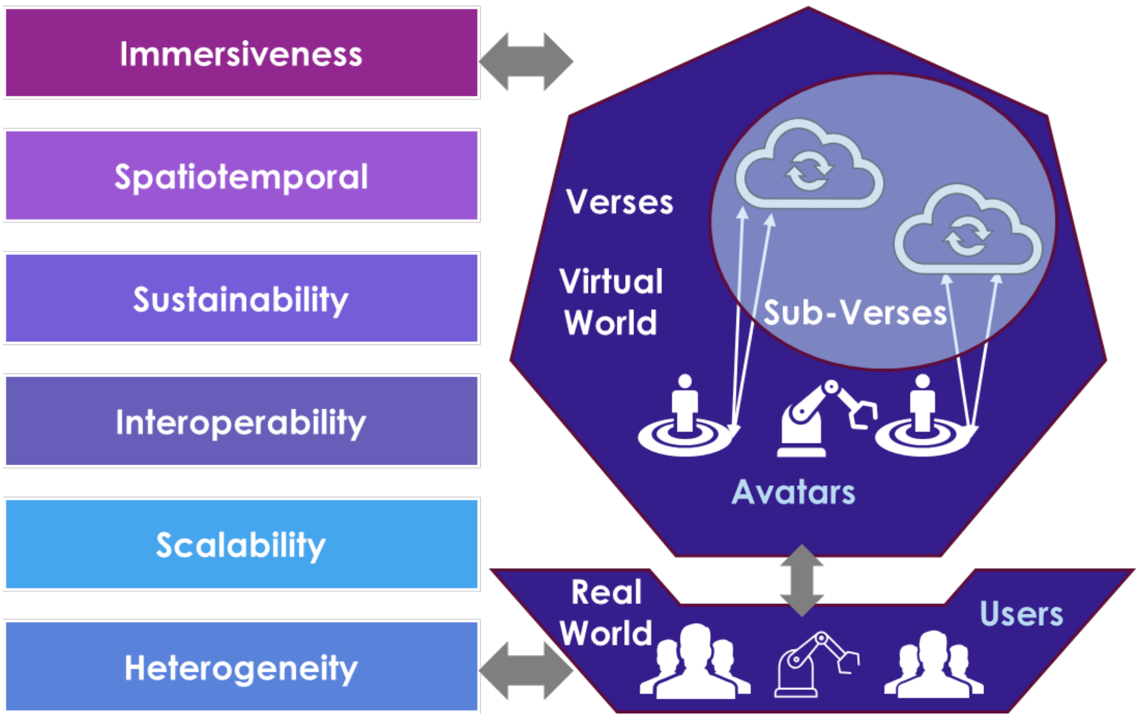

Figure 3-4 Verses characteristics. Source: Adapted from [8]

The metaverse integrates a sense of immersion, real-time interactivity, and user instruments while including platforms and devices that work seamlessly with each other, multiple people and machines that interact simultaneously, and use cases across sectors. The metaverse embraces and augments reality with virtual content and experiences that can enhance the experiences in virtual spaces.

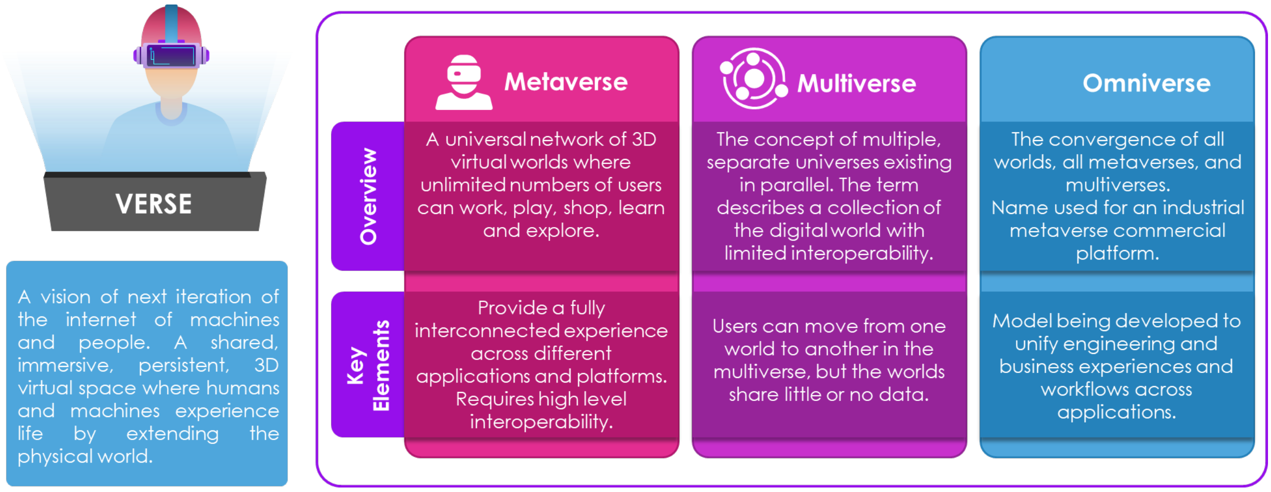

Figure 3-5 The concept of verses in the context of immersive technologies.

A metaverse is a digital universe created by converging enhanced physical and persistent virtual reality. The metaverse describes virtual worlds, where users, represented by avatars, engage in 3D environments, performing interactions to build social and economic connections [18]. This concept originated in Neal Stephenson's 1992 science fiction novel "Snow Crash," which portrays an immersive virtual realm [38]. In "Snow Crash," the metaverse is imagined as a future version of the Internet, a unified and immersive virtual world enabled by VR and AR headsets. These virtual worlds are computer-simulated environments inhabited by users who can create personal avatars. Users independently explore, participate in activities, and communicate within these spaces. Avatars can range from textual and graphical representations to live video avatars with auditory and tactile feedback.

The metaverse is an interdisciplinary concept as illustrated in Figure 3-6 that encompasses an interconnected network of shareable and persisting virtual worlds, AR, and the Internet that allows end users to experience a sense of social presence and spatial awareness in a three-dimensional virtual space and participate in an extensive virtual economy. The metaverse concept is often associated with science fiction and VR but is also being developed as a potential future reality. Various technologies such as VR/AR, 3D modelling and animation SW, game engines, cloud, and edge computing, blockchain, intelligent connectivity networks, AI and ML are utilised to create and support a metaverse.

The industrial metaverse welds physical-digital-cyber fusion and human augmentation for industrial applications. It incorporates digital representations of physical industrial environments, IoT devices, systems, assets, and spaces that people manage, control, communicate and interact with.

These technologies continue to develop and improve as the metaverse progresses allowing for creating immersive brand experiences or virtual storefronts, allowing people and machine to interact with each other in a new way, facilitating remote collaboration and communication and share information seamlessly regardless of location.

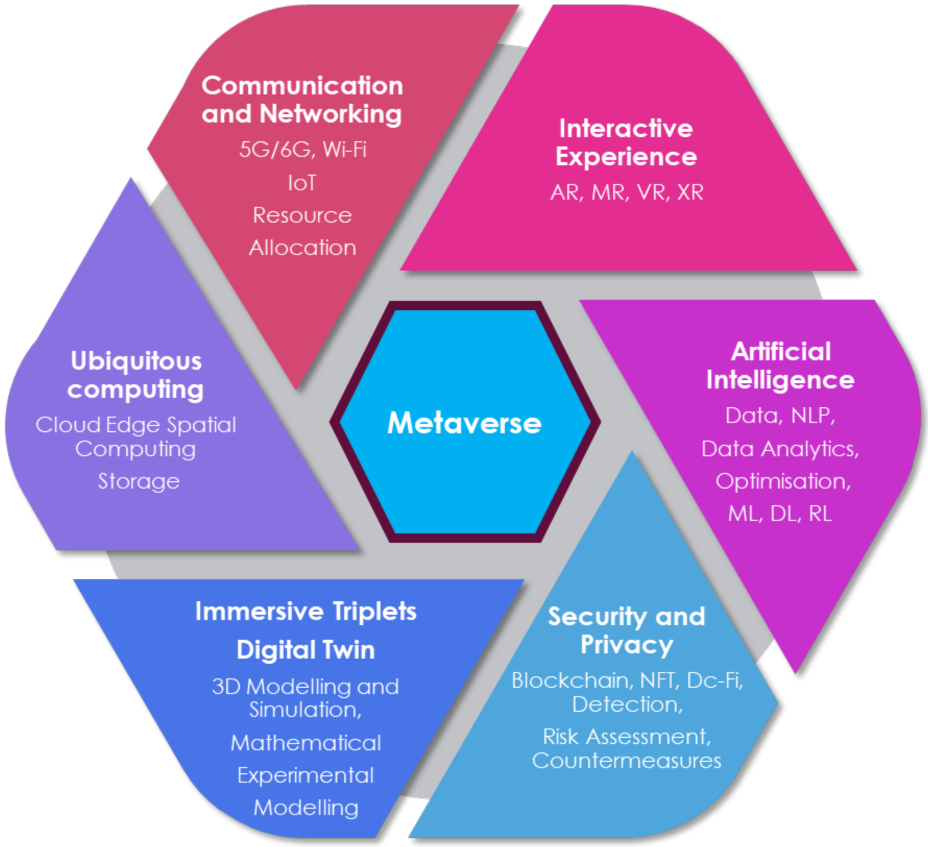

Figure 3-6 Metaverse interdisciplinarity.

The idea of the metaverse that postulates as a hypothetical iteration of the Internet as a single, universal, and immersive virtual world is facilitated by other immersive technologies such as AR, VR, MR. A metaverse is a network of 3D virtual worlds focused on social connections. It is an open, shared, and persistent virtual space where users can be digital avatars. The premise of the metaverse is that users can do everything in the virtual world that they can do in the real world. The metaverse combines concepts of immersive technologies (VR, AR) and digital second life.

The metaverse is a collection of every virtual world built using blockchain technology. These include gaming planets, NFT galleries, curated lands, or digital streets. The NFTs are blockchain-based tokens that each represent a unique asset designed to be cryptographically verifiable, unique, or scarce and easily transferable. An NFT can be considered an irrevocable digital certificate of ownership and authenticity for a given digital or physical asset. The metaverse is not one place; it is a collection of novel digital spaces that people and machines call the next iteration of the Internet. The metaverse differs from online social platforms in terms of the space between centralisation and decentralisation. Metaverse develops digital spaces that allows users to use a single identity to travel across and through the growing network of virtual landscapes. This makes it more like a mirror of the real world.

The term metaverse is widely used across various fields, including technology, gaming, social media, and academia. However, it had yet to be formalised by a universally accepted standardized definition. The metaverse concept can be defined as a collective virtual shared space created by the convergence of virtually enhanced physical reality, persistent virtual spaces, and the Internet. It represents an expansive network of 3D virtual worlds and simulations that support the continuity of identity, objects, history, payments, and entitlements.

Key characteristics and components associated with the metaverse include: (i) persistence, as the metaverse operates continuously and continues to evolve and exist; (ii) interoperability, which allows assets, information, and data to be seamlessly transferred and utilized across different virtual environments and platforms within the metaverse; (iii) immersive experience that can include VR, AR, and other technologies to make digital interactions feel as authentic as possible, social interaction where users both humans and machines can meet, collaborate, and interact with each other in a variety of contexts, accessibility through a wide range of devices, including VR headsets, AR glasses, edge IoT devices, allowing users to access its content from anywhere.

In the metaverse, humans and users can create and contribute their own content, experiences, and environments within the metaverse, often with few limitations on creativity. As the idea of the metaverse continues to evolve, industry consortia and standard developing organisations play key roles in defining the protocols, standards, and guidelines that will underpin its implementation and governance.

AI is instrumental in the development and operation of the metaverse. It allows for the creation of highly realistic and engaging virtual worlds, ensures optimal performance, enhances security measures, and provides users with personalised experiences.

AI enhances the metaverse by allowing for the creation of realistic and interactive virtual worlds. AI can be used to create virtual characters that can interact with users in a lifelike manner and to develop virtual economies, tracking user behaviour and analysing data to create virtual marketplaces and tailor virtual worlds to each user's interests and preferences, providing a more personalised and engaging experience.

AI can manage and optimise the metaverse's performance. It can monitor and analyse data to identify and resolve bottlenecks, ensuring smooth user experiences. AI enhances security within the metaverse. It can identify and prevent potential security threats, such as hacking or fraud, helping to ensure that the metaverse remains a safe and secure place for users.

A particularly impactful use case of the metaverse is in the industrial sector. This involves the integration of digital twins, AI, and IoT within the industry, opening new avenues for innovative industrial applications with significant potential. In industrial settings, the metaverse enables unmatched operational agility and precision as illustrated in Figure 3-7.

The industrial metaverse facilitates real-time monitoring and control of production lines, predictive maintenance through AI-driven insights, and remote virtual simulation of manufacturing processes using VR equipment in complex manufacturing ecosystems. This dramatically minimises downtime while improving performance and ensuring quality control. Additionally, by utilising VR/AR, companies can perform remote training and equipment troubleshooting, enabling experts to assist onsite technicians with complex repairs or procedures without travelling, thus saving time, and reducing carbon emissions.

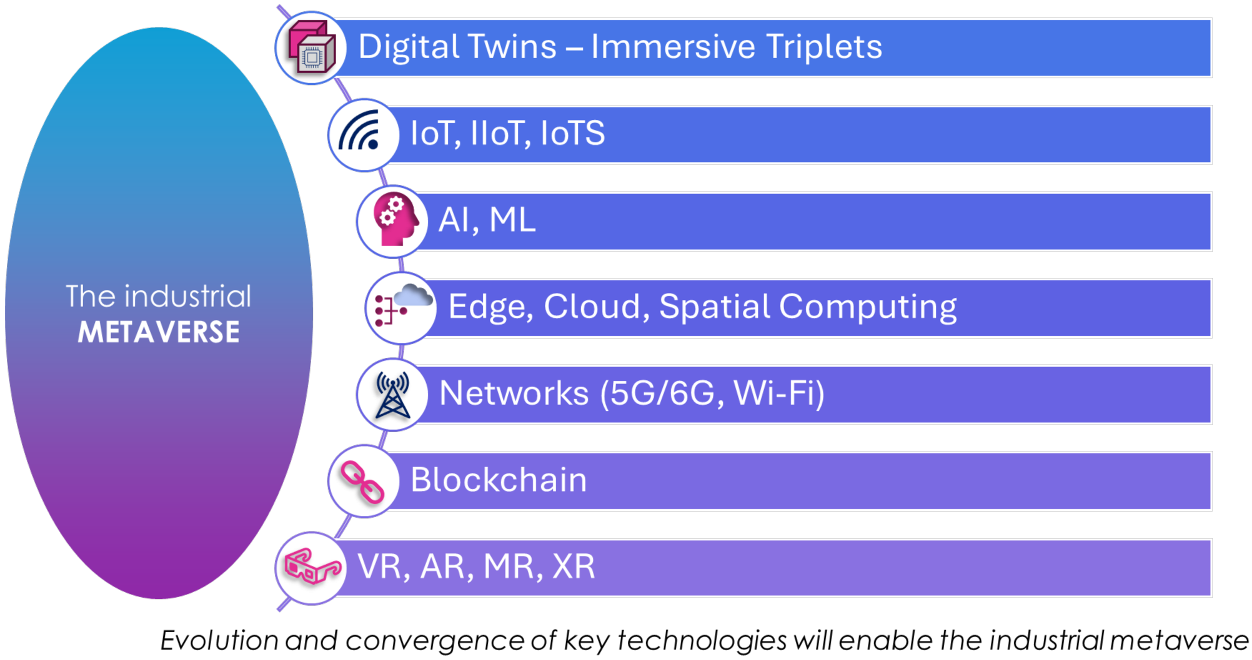

Figure 3-7 The industrial metaverse. Source: Adapted from [37].

Furthermore, the industrial metaverse provides a collaborative platform for product development and innovation, connecting engineers, designers, and stakeholders across different locations. It supports the co-creation and testing of prototypes in a virtual environment, significantly reducing the design cycle and enhancing the capacity for rapid innovation in response to market changes.

The virtual collaboration goes beyond product development to include entire supply chains, creating a synchronised digital thread that allows for real-time data and analytics to optimise logistics, minimise waste, and prevent supply chain disruptions before they happen. As industries aim for a more sustainable and efficient future, the industrial metaverse is a critical technology, revolutionising how companies operate, innovate, and compete in a digital-first world.

2.6 Omniverse

The term omniverse refers to a collection of every verse, multiverse, or other possible realities suggesting an even more expansive and interconnected digital verses and platforms than what metaverse implies.

In a technical or scientific context, the omniverse refers to platforms for collaborative simulation and design that allow for real-time, physically accurate simulation of diverse 3D workflows. It is designed to serve as a unifying platform for connecting 3D workflows in a shared virtual space, allowing designers, creators, and engineers to collaborate in real-time across various SW suites.

Even the omniverse is not standardised, it emphasises interoperability between different SW tools, facilitating a seamless exchange of information and assets. The omniverse uses real-time simulation and rendering for complex scenes and simulations, leveraging advanced graphics and AI accelerator technologies.

The omniverse concept is considered extensible, allowing developers to build custom applications, add-ons, and services that integrate with the platform, further enhancing its utility and scope. In the broader sense, the term omniverse can refer to a comprehensive and interconnected set of digital realities extending the metaverse, potentially incorporating not just virtual worlds and augmented realities but also advanced simulations, AI-driven environments, and more.

Omniverse is used across industries for collaboration and real-world infrastructure simulations. It integrates immersive triplets and avatars, serving as a platform for design collaborations and creating realistic simulations of industrial environments. "Omni" signifies "all," blending the metaverse with the multiverse. Here, the multiverse forms the basis for the metaverse, with the omniverse acting as a comprehensive shield over the digital experiences offered by both the metaverse and multiverse. It merges economic and digital identities, profoundly transforming how we interact on the future Internet and Web 4.0.

The omniverse encompasses all metaverses and multiverses, whether interoperable or not, striving to broaden these verses through innovative interoperability approaches. It is an expandable platform that allows users to develop custom 3D pipelines and simulate expansive virtual worlds. This includes an ecosystem and marketplace specialising in tools, AI models, simulation models, and business workflows for various verses.

The omniverse amalgamates all existing metaverses, multiverses, and the physical worlds of the users. It forms a vast, all-encompassing network of interconnected dimensions and possibilities, transitioning from isolated platforms competing for users and revenue to a decentralised infrastructure. In this setting, the omniverse represents a broader spectrum, encompassing various realities and dimensions beyond multiple universes. It embodies the aggregate of all real and imagined universes: the ultimate reality encompassing the universe, parallel universes, and fictional universes are all situated here.

2.7 Multiverse

The term multiverse in the context of digital environments and immersive technologies describes a vast array of disconnected or loosely connected virtual worlds, platforms, and digital spaces. In the digital context, the focus is on the diversity and plurality of digital experiences rather than the existence of parallel universes.

The multiverse characteristics in digital contexts refer to the collection of virtual worlds based on various virtual environments that users can explore and interact with. Unlike a single, unified virtual world, the multiverse encompasses many such worlds, each potentially with its own rules, themes, and user experiences.

Despite the distinctiveness of each virtual world, there is often a level of interconnectedness that allows for the transfer or continuity of user identities, assets, or information across these virtual spaces. This interconnectedness can vary in its implementation and may not be as seamless or integrated as the concept of the internet.

The multiverse concept leverages immersive technologies like VR, AR, and MR to enhance the user's sense of presence within these digital spaces.

Diversities of experiences are key features of multiverses, appealing to a broad user base with varied interests. Many multiverse environments incorporate their economic systems, using digital currencies or tokens to facilitate trade, purchase virtual goods, or monetise content and experiences.

These economies can be complex and multifaceted, with real-world value and implications. The multiverse emphasises user-generated content, allowing users to create, modify, and control virtual spaces, objects, and experiences. This democratisation of content creation fuels the diversity and expansiveness of the multiverse.

The multiverse concept reflects the evolution of online and virtual experiences towards more richly detailed, user-centric, and interconnected digital lives.

As technology advances, the boundaries between different virtual environments may become more fluid, enabling users to navigate between worlds easily and bringing the digital multiverse closer to realisation. This vision aligns with broader trends in technology development, including the growth of the metaverse and the increasing integration of digital and physical realities.

The concept of a "multiverse" in digital terms, envisioned as a network of interconnected virtual spaces, heralds the advent of Web 4.0 technologies. The multiverse aims to create various interconnected virtual environments, from the entirely digital realms to simulations of the physical world, all accessible through immersive technologies. These environments are designed for multiple uses, such as industrial manufacturing, entertainment, education, remote work, and social interactions.

As Web 4.0 technologies evolve, they enable seamless transitions between different virtual environments or layers of VR, AR, MR and XR through advanced networking and real-time data streaming technologies, enhanced by edge computing to reduce latency.

Integrating IoT, edge computing, AI, and immersive technologies into the multiverse and Internet Web 4.0 environments marks an exciting frontier. This convergence is set to revolutionise how humans and machines perceive and interact with digital content, enriching our virtual experiences to be more meaningful, personalised, and connected to the physical world.

2.8 Spatial Web 4.0 - Internet of Humans and Machines Evolution

This paper uses the terms Internet and World Wide Web (Web). The Internet is defined as a global computer network providing a variety of information and communication facilities, consisting of interconnected networks using standardised communication protocols.

The Web is one of the essential services offered by the Internet and one of the ways that information is shared over the Internet. The characteristics that define the Internet and the Web are presented in Figure 3-8.

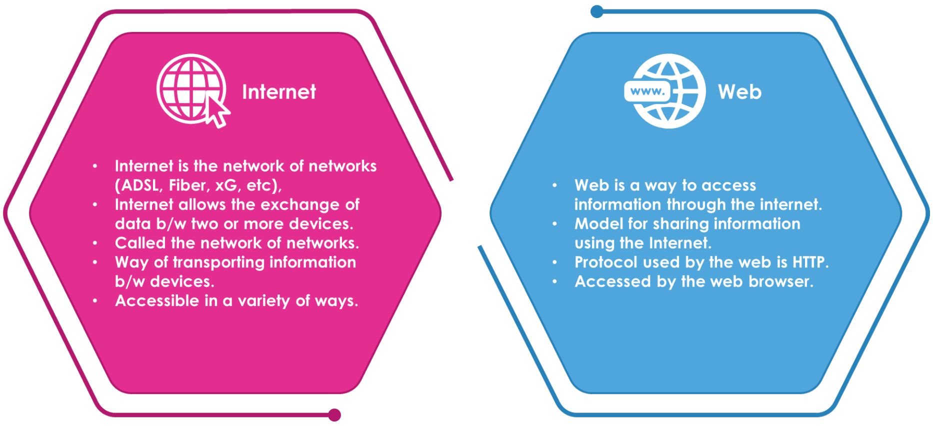

Figure 3-8 Internet and Web characteristics.

The Web has evolved extensively, from basic websites with static text and images to advanced web applications capable of personalised experiences and complex functionalities, as illustrated in Figure 3-9.

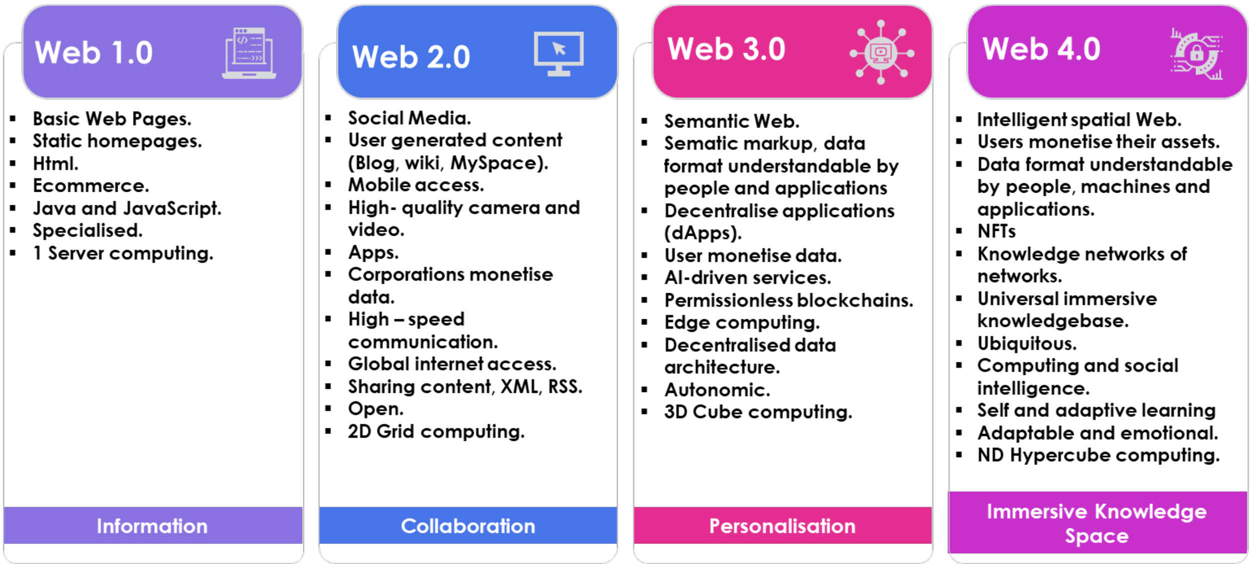

Figure 3-9 Web evolution.

Web 4.0 is the fourth generation of the World Wide Web, which is focused on integrating AI, the semantic web, humans, and machines creating an innovative and development platform for edge IoT technologies and applications. Web 4.0 integrates advanced AI and ambient intelligence, the IoT, DLTs, trusted blockchain transactions including NFTs, virtual worlds, XR capabilities, digital and real objects and environments thoroughly combined and communicating to enable genuinely intuitive, immersive experiences that seamlessly blend the physical and digital worlds. Web 4.0 creates an entirely new type of web combining spatial web with spatial computing, thus building a future where people and machines can live, play, and work better together.

With Web 4.0 technologies, is expected to enable more intelligent and interactive applications and more seamless communication between humans and machines. VR, AR, and XR are all technologies that allow users to experience digital content in more immersive ways.

Web 4.0 encompasses platforms and applications facilitating the transition towards a decentralised Internet of tomorrow, characterised by open standards and protocols safeguarding digital ownership rights. It gives participants greater data ownership and control over monetising their data and catalyses new business models.

Decentralised databases and SW programs (e.g., smart contracts) open-source code, immutable public data, public-private key cryptography. and composability (e.g., the ability to fork and integrate on top of existing projects) are part of the envisioned Web 4.0.

Web 4.0 represents a new stack of technologies for developing decentralised web applications enabling users to control their identity and data. These technologies involve blockchain as a trust verification mechanism, privacy-preserving and interoperability protocols, decentralised infrastructure and application platforms, decentralised identity, and support for applications like decentralised finance, which is the next step for implementing a decentralised web.

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Web 4.0 envisions what the Internet could look like, built on new types of technology like blockchain, a digitally distributed, decentralised ledger across a computer network. Blockchain facilitates the recording of transactions as new data are added to a network. New blocks are created and appended permanently to the chain. All nodes on the blockchain are then updated to reflect the change. This means the system is not subject to a single point of control or failure.

Smart contracts are SW programs automatically executed when specified conditions are met, such as buyer and seller agreeing on terms. They are established in code on a blockchain that can't be altered.

Digital assets and tokens are items of value that exist only digitally. They can include cryptocurrencies, stablecoins, central bank digital currencies (CBDCs), and NFTs. They can also include tokenised versions of assets, including real things like art or tickets to concerts or sporting events.

Web 4.0 refers to decentralised databases and systems architecture, whereas the verses are new computing and networking paradigms. The Web 4.0 and verses may grow in what is experienced as the Internet today, but there's a long way to go before that can happen.

Web 4.0 expands on cryptocurrency, employing blockchain in novel ways for different purposes. A blockchain can record token quantities in a wallet, conditions of a self-executing contract, or the code for a decentralised app (dApp). Blockchains are "append-only," meaning once information is written to the blockchain, it is not possible to alter or delete it.

Web 4.0 and cryptocurrencies run on "permissionless" blockchains, which have no centralised control and don't require users to trust or know anything about.

The synergy between Web 4.0 and immersive technologies such as VR, AR, and MR is paving the way for transformative experiences across various sectors. Web 4.0, with its decentralised architecture, provides a robust foundation for building immersive experiences that are more democratic, secure, and user-centric.

The blockchain technology of Web 4.0 enables decentralised ownership and control over digital assets and experiences. In immersive environments, users can own their virtual assets, such as avatars, digital clothing, or virtual real estate, which are securely managed and transferred on the blockchain. This opens new economic models in virtual worlds, including trading, leasing, or monetising digital properties and creations.

One of Web 4.0's core principles is interoperability, which is the ability of different systems and organisations to work together. Immersive technologies facilitate interoperability by enabling users to move seamlessly between different virtual environments or platforms with their digital identities and assets intact. This could allow for a unified, expansive virtual universe where assets and experiences are not siloed but part of a larger, interconnected ecosystem.

The decentralised nature of Web 4.0 offers improved security and privacy for users in immersive environments. The secure, and tamper-proof ledger of blockchain technology ensures that transactions and data exchanges in virtual spaces are recorded securely and with transparency, minimising fraud risk and data breaches.

Decentralised identity solutions can give users control over their personal information, allowing them to share data selectively and securely in virtual interactions. Web 4.0 technologies empower communities to create, govern, and evolve their virtual spaces collectively and the rules that govern them. Through decentralised autonomous organisations (DAOs), participants in virtual worlds can make decisions on the development of the platform, manage shared resources, and shape the social and economic policies of their digital environments.

Immersive technologies benefit from Web 4.0 trust and security features to offer experiences that are not only visually and sensorially compelling but also profoundly engaging through real ownership, economic participation, and social interaction. This can lead to more meaningful and sustained engagement in virtual spaces, as users are not just passive consumers but active participants in these digital ecosystems.

The synergies between Web 4.0 and immersive technologies are unlocking new possibilities for virtual experiences, redefining how we interact with digital content, engage with communities, and transact in virtual environments. As these technologies advance, they are likely to create more immersive, interactive, and inclusive virtual worlds that closely mirror the complexity and richness of the physical world.

Web 4.0 embodies a new era of the Internet, conceived as a decentralised online ecosystem founded on blockchain technology. Unlike the present Internet version (Web2), dominated by centralised platforms and services owned by a handful of large corporations, Web 4.0 aims to return control and ownership to the users.

The technological advances it brings have the potential to profoundly change the way one interacts with the digital realm, creating a more open, transparent, and user-empowered internet.

The future of technology, particularly with the convergence of IoT, edge computing, AI, and industrial immersive technologies, is poised for groundbreaking developments, especially when integrated with emerging concepts like the metaverse, the omniverse, the multiverse, and Internet Web 4.0. This future version of the Internet is expected to be more autonomous, intelligent, and seamlessly integrated into everyday objects. It could leverage blockchain for security and decentralisation, facilitate microtransactions within the various verses, and support sophisticated AI-driven interactions.

The convergence of these technologies signifies a technological shift, as well as a cultural and economic one, potentially altering how we perceive and interact with the digital and physical worlds. This convergence promises a more integrated, immersive, and interactive future.

4. Industrial Immersive Enabling Technologies Convergence

The convergence of industrial immersive enabling technologies refers to the integration and synergistic application of various advanced technologies to create immersive, interactive, and highly efficient industrial environments. The goal is to enhance operational efficiency, improve safety, security, and foster innovation in industrial settings.

In industrial immersive environments, edge computing provides the mechanisms for distributing data processing and redefines the IoT landscape by moving data processing and analytics at the edge by using AI/ML techniques and ensuring an advanced level of embedded security.

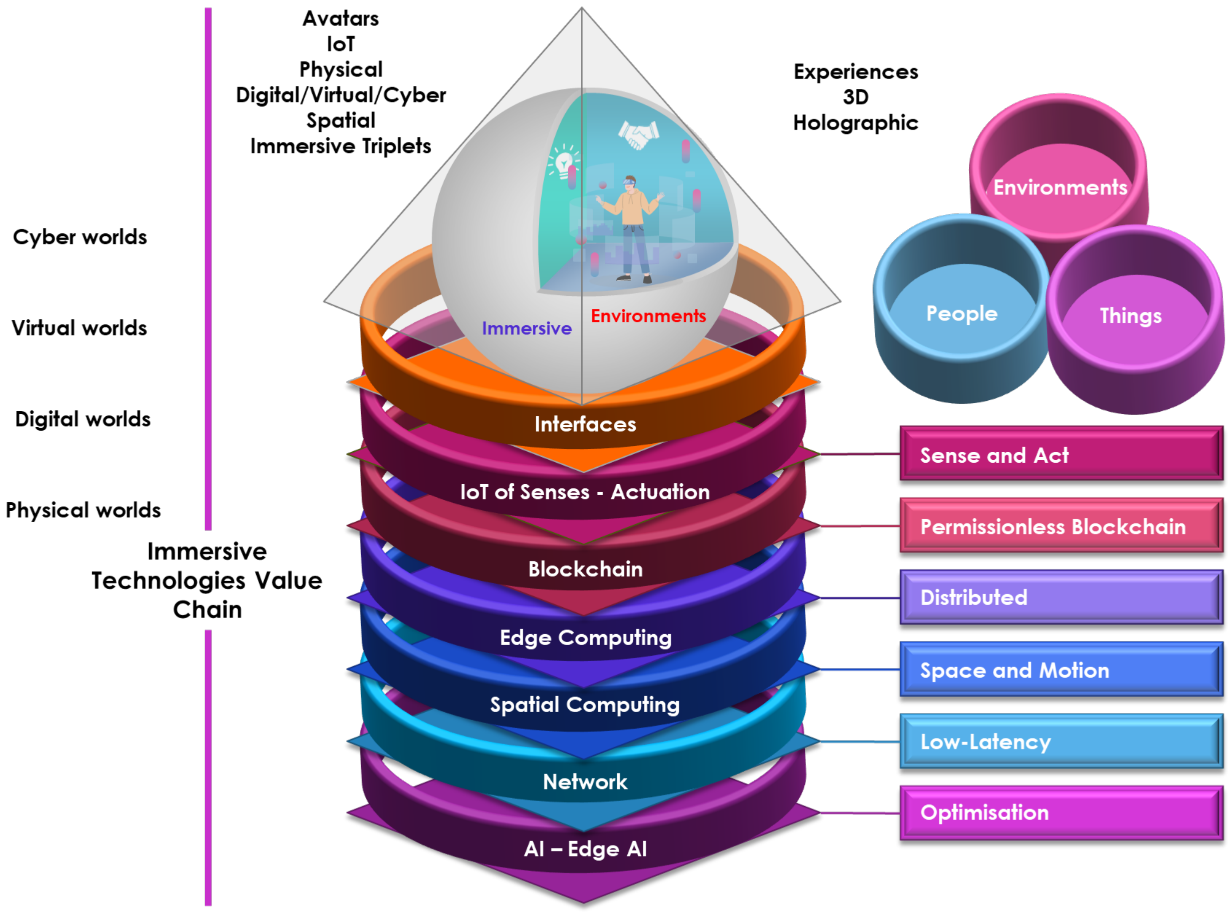

Figure 4-1 Edge immersive technologies convergence across the value chain.

Edge computing is a key ingredient of industrial immersive technologies that allows an effective deployment of real-time applications, considering that the processing is performed close to the data source. It also reduces the order of magnitude of transmitted data, by not transmitting the extensive amount of raw data created by IoT devices, rather just sending smaller amount of data, thanks to storage and local processing capabilities.

3.1 Internet of Things

IoT represents a dynamic global network infrastructure endowed with self-configuring capabilities, utilizing standard interoperable communication protocols. This network integrates physical and virtual "things" - each possessing unique identities, physical characteristics, and virtual personalities - through intelligent interfaces, enabling seamless integration into the information network. In this ecosystem, "things" actively participate in business, informational, and social processes, capable of intercommunication and environmental interaction.

They autonomously react to real-world events and influence outcomes by executing processes that trigger actions and generate services, with minimal or no human oversight. Service-oriented interfaces facilitate these interactions by allowing remote querying and modification of their states and related information, all while addressing security and privacy concerns.

In the context of industry digitisation, IoT and Industrial IoT (IIoT) merge key attributes of advanced Internet technology, mobile systems, and pervasive connectivity with industrial control functionalities, including sensing, actuating, and controlling. Interoperability, platform integration, and standardisation are crucial in the digitization of industrial applications. IoT, IIoT, and industrial control systems incorporate essential attributes like integrity, availability, and confidentiality, crucial for application deployment within and across various industrial sectors.

Edge computing is defined as a paradigm that can be implemented using different architectures built to support an IoT distributed infrastructure of data processing (signals, image, voice, etc.) with edge IoT devices operating close to the points of collection (data sources) and utilisation. The edge computing distributed paradigm provides computing capabilities to the IoT nodes and devices of the edge of the network (or edge domain) to improve the performance (energy efficiency, latency, etc.), operating cost, security and reliability of applications and services. Edge computing performs data analysis by minimising the distance between IoT nodes and devices and reducing the dependence on centralised resources that serve them while minimising network hops.

IoT edge computing capabilities include a steady operating procedure across different platform infrastructures to deliver processing services to remote IoT devices, application integration, orchestration, and service delivery requirements. The edge computing technologies are meant to properly consider HW limitations and cost constraints, to effectively handle limited or intermittent network connections, and to implement methods to satisfy the most diverse requirement sets, e.g., IoT applications requiring low latency or greatly differing in data rates.

For intelligent IoT applications, the edge computing concept is mirrored in the development of different edge computing levels (micro, deep, meta), that incorporate the computing and intelligence continuum from the sensors/actuators, processing units, controllers, gateways, on-premises servers to the interface with multi-access, fog, and cloud computing.

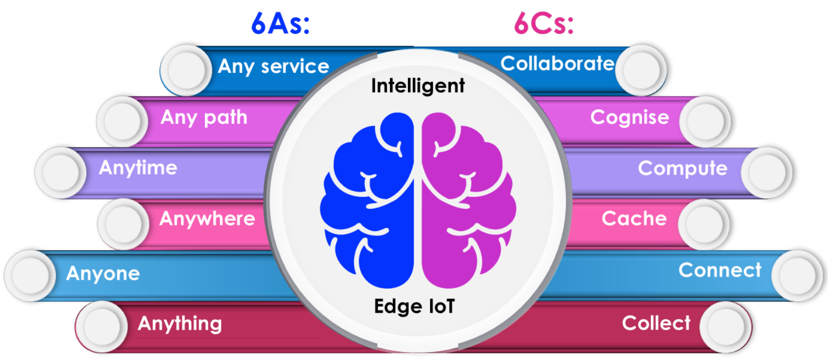

Figure 4-2 Edge IoT key attributes characterised by 6As and 6Cs.

Edge IoT and industrial immersive technology developments are characterised by six key attributes, collectively known as the 6**A**s: **A**nything (any device) transferred from/to **A**nyone (any person/machine), located **A**nywhere, at **A**nytime (in any context), using **A**ny path (any network) for optimal connectivity based on performance and economic considerations, all to provide **A**ny service (any business). The intelligent edge IoT paradigm has evolved, leading to the creation of IoT ecosystems built on foundational elements termed the 6**C**s: **C**ollect (diverse devices of varying complexity and intelligence enhance real-time data collection), **C**onnect (ubiquitous connections between these diverse devices and data), **C**ache (data storage within distributed IoT computing environments), **C**ompute (advanced data processing), **C**ognise (analytics and real-time AI processing), and **C**ollaborate (creating/developing new interactions, services, and business models through collaboration) [41][40].

The IoT transforms everyday objects into rich ecosystems of information that enhance our lives. It influences the future Internet landscape, impacting security and privacy while potentially narrowing the digital divide. As AI and IoT increasingly rely on network connectivity, their vulnerability to security threats grows. The AI in IoT market size was estimated at USD 9.17 billion in 2023, USD 10.75 billion in 2024, and is expected to grow at a CAGR of 17.35% to reach USD 28.11 billion by 2030 [50].

The future success of the Internet as a driver of economic and social innovation hinges on how these new technologies tackle such challenges. Integrating AI with IoT opens new opportunities, from scientific breakthroughs to enhancing human intelligence and merging it with the physical and digital realms. The convergence of IoT with technologies like AI, DLTs, hyperconnectivity, distributed edge computing, and autonomous systems requires heightened human-centric safeguards and ethical considerations in their design and implementation [40].

The IoT bridges the gap between the virtual, digital, and physical realms by integrating people, machines, processes, data, and things, generating knowledge through IoT applications and platforms. It addresses security, privacy, and trust issues across these dimensions in a time of increasing technology, computing power, connectivity, network capacity, and smart device proliferation. IoT is a key driver of digital and immersive transformation in this context.

The primary added value of IoT/IIoT and edge computing is the contextualisation and onboarding of the immersive technologies in the industrial sectors. The intelligent edge IT devices used in immersive environments are equipped with sensing, connectivity, processing, and analytics to understand complex situations by aggregating information, applying AI patterns and incorporating user behaviour. This allows the decision-making processes to be aligned with a local, global context, visualise the event and add a graphical animation of actual and future scenarios.

Intelligent connectivity, edge computing and IoT are shaping the future of immersive technologies. Thanks to higher bandwidths, flexible external computing capacities, industrial immersive applications are emerging in various industrial sectors.

IoT connects physical and virtual worlds. Data from IoT-enabled devices is collected, converted into information, and made visible in real-time through interactions in physical, digital, virtual, cyber, and spatial environments. Immersive technologies represent the IoT, by augmenting the world with information derived from the IoT or even immersing humans and machines in the new created spatial environments.

3.2 Internet of Things Senses

The notion of "senses" within the context of IoT likely refers to the extension and enhancement of IoT capabilities through advanced sensory technologies that mimic human senses such as sight, hearing, touch, smell, and taste. These sensory technologies enable IoT devices to perceive their environment nuancedly, leading to more sophisticated data collection, interpretation, and interaction capabilities in immersive contexts.

Sight (Vision): This sense is mediated by vision sensors, which enable one to perceive light, colours, shapes, and movements. It's essential for navigating our environment and recognising objects and individuals. Cameras and image recognition technologies allow IoT devices to see their environment. This can be used in applications such as immersive systems, autonomous, and quality control in manufacturing.

Hearing (Audition): Hearing is the ability to perceive sounds by detecting vibrations. It's crucial for communication through language, recognising sounds in the environment. Microphones and advanced sound processing technologies enable devices to hear and respond to audio cues.

Taste (Gustation): Taste is the ability to detect flavours in substances, including sweetness, sourness, saltiness, bitterness, and umami (savoury). It's vital for tasting food and drinks and for avoiding harmful substances. This is an evolving sense in IoT and emerging in areas like environmental monitoring and food safety.

Smell (Olfaction): The sense of smell allows us to detect and differentiate odours. It's closely linked to taste and memory, significantly influencing the perception of flavours and emotional memories. The IoT advances include sensors capable of detecting chemical compositions or specific gases that mimic the human senses of smell.

Touch (Tactile Sense): Touch is the ability to perceive pressure, temperature, and pain. It's essential for physical interaction with the environment and connection with humans, animals, things, and other machines. Sensors that detect pressure, temperature, or vibration allow IoT devices to "feel" physical interactions in immersive environments. This sense is crucial for wearables, IoT devices, and robotics in real and immersive environments, e.g., in human-human collaboration or human-robot-interaction.

Tactile IoT is formed by networks that combine ultra-low latency with extremely high availability, reliability, and security, enabling the delivery of physical sensations or tactile experiences remotely in real and immersive environments in real-time through advanced haptic technologies and high-speed networks.

Balance and Spatial Orientation (Vestibular Sense): Vestibular sense helps maintain balance and spatial orientation. It's governed by the detection of position in relation to gravity and movement.

The sense of sight is crucial in connecting perception to physical reality, whereas hearing offers additional proof of what's real. When further verification is needed beyond sight and sound, one naturally seeks to touch the object for closer examination. Touch provides the definitive perceptual experience to affirm reality, and this sense of immersion can be enhanced through advanced media and sensory technology. The Figure 4-3 illustrates the extension of the use of senses and the models developed to provide information and improve the immersive experience with more multi-sensory communication and intelligence.

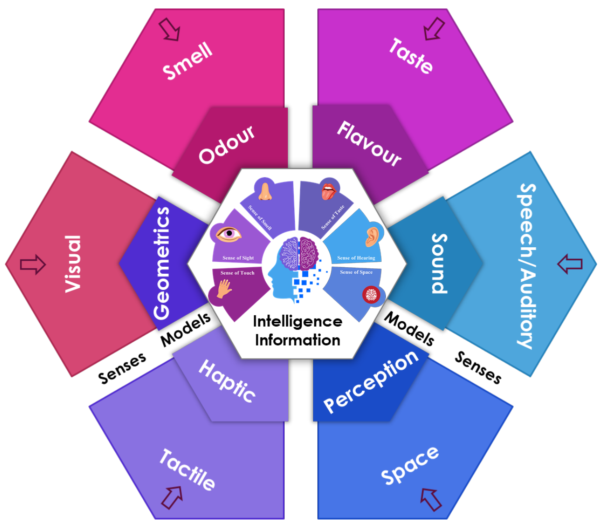

Figure 4-3 Edge immersive multi-sensory communications for providing information and intelligence.

Humans have additional senses, including proprioception (the sense of body position and movement), thermoception (the sense of temperature), and nociception (the sense of pain).

IoTS in immersive applications need to ensure interoperability, reliability, and security in IoT applications reflecting the advancements and integrations of sensory capabilities within the immersive IoT edge ecosystem, enabling users to experience and manipulate objects in a virtual or remote environment as if they were directly interacting with them.

Haptic technology is part of the evolution of the IoTS, integrating immersive technologies with devices and algorithms capable of generating touch sensations, including force feedback and texture simulation, allowing users to feel the shape, texture, stiffness, and other properties of virtual objects.

The use of haptic technology for touch-based social interactions is called social touch technology (STT). It addresses circumstances where human communication partners engage in social touch mediated through technology and situations where humans interact with artificial social agents (virtual) that can respond to applying social touches. For advanced immersive applications, haptics to multi-sensory communications is complemented by mixing haptics sensing and actuation with other modalities, such as vision and sound, in a VR/AR context [19].

Table 4-1 Actuation and modalities within a multi-sensory communication for mediated social touch [19].

Meaning	Type of touch	Body Location	Modalities	Actuation
Affection	Abstract, Contact, Hug, Squeeze, Stroke, Kiss, Press, Tickle	Hand, Abdomen, Leg, Arm, Chest, Torso, Back, Side, Lips	Touch, Vision, Audition	Vibrotactile, Temperature, Force
Greeting	Handshake	Hand	Touch, Vision, Audition	Temperature, Force
Inclusion	Holding Hands	Hand	Touch	Temperature, Force
Playful Aggression	Arm Wrestling	Hand	Touch	Force
Symbolic	Abstract, Poke	Hand, Cheek, Finger, Arm	Touch, Vision, Audition	Vibrotactile, Force

The Table 4-1 shows the types of actuation and modalities communicated to reflect different types of social touch and meanings.

3.3 Internet of Things Digital Twins Evolving to Immersive Triplets

The expansion of immersive technologies transforms DTs into immersive triplets, defined as the dynamic spatial, digital, and virtual representations of a physical object or system, spanning their lifecycle, and updating from real-time conditions and spatial data. They use immersive environments, simulation, ML, and reasoning to assist decision-making and create real-time avatars for immersive applications.

The convergence of IIoT, AI, ML, DTs, and IMTs combined with XR are the backbone for the development of the industrial metaverse by increasing the intelligent capabilities of the elements in the immersive industrial spaces and changing how digital models and physical products interact using SDA in the future industrial processes and Industry 5.0.

Immersive triplets integrate IoT, edge and spatial computing, AI, ML, and software analytics with spatial network graphs to create living immersive simulation models that update, change, and move in space as their physical counterparts change. The key components of the immersive triplets include real-time data integration to accurately replicate IoT edge devices in a virtual 3D space. This data includes operational data, environmental conditions, physical parameters, spatial coordinates, and other relevant information.

As part of the immersive environments and various verses, the immersive triplets apply complex simulations and models that can predict future states, conduct analyses, and optimize systems through simulations before physical changes are made.

They cover the entire lifecycle of their physical counterparts, from design and development through operation to decommissioning, providing valuable insights at each stage. Effective immersive triplets can integrate with other immersive systems and platforms, ensuring data flows seamlessly between different application areas.

IMTs advance immersive technologies by providing a detailed, real-time digital, virtual, and spatial replica of physical objects, processes, systems, or environments. These virtual spatial models are not static; they are updated from real-time data, enabling them to accurately simulate the current state of their physical counterparts. Integrating IMTs with immersive technologies like VR, AR, and MR drives innovation across various sectors.

By incorporating real-time data into immersive environments, IMTs make VR and AR experiences more realistic and interactive. Users can explore and interact with virtual replicas that reflect the status of the physical world, including dynamic changes and real-time feedback. IMTs in immersive environments enable remote teams to collaborate more effectively by interacting with the same virtual model from different locations and spatial contexts.

In an industrial context, NFTs can represent physical assets (e.g., IoT devices, machines), digital assets (SW, data), or intellectual property. The blockchain's immutable ledger ensures that each asset's history, from creation through various ownerships or changes, is permanently recorded and easily verifiable.

NFTs are used to create and manage IMTs and DTs of physical assets, including monitoring, simulation, and control. IoT devices and their immersive triplets and digital twins can track and record real-time asset use, condition, and location data. When paired with NFTs, this data becomes part of the asset's unique digital footprint on the blockchain, enhancing traceability and security.

By processing data at the edge, closer to where it's generated, companies can quickly update an NFT's status to reflect real-time changes, which is crucial for dynamic and high-value asset management.

Edge AI algorithms can analyse data from immersive triplets and DTs to optimise performance, predict maintenance needs, and enhance operational efficiency. NFTs ensure that the data and models are uniquely linked to specific assets, adding a layer of security and authenticity.

Integrating NFTs with IoT, edge computing, AI, and blockchain technologies with immersive triplets and DTs holds significant potential for transforming industrial operations, supply chains, and digital asset management. This convergence enhances operational efficiency and transparency and opens new avenues for asset utilisation and value creation in industrial immersive technologies.

The synergy between immersive triplets and immersive technologies creates opportunities for more interactive, accurate, and efficient applications across various sectors. By bridging the gap between the physical and digital worlds through 3D spatial representation and real-time stamp, this integration enhances the realism and applicability of immersive experiences and unlocks new potentials for innovation, collaboration, and learning.

3.4 Virtual Replicas with Active Force Feedback

Integrating active force feedback mechanisms can enrich systems such as immersive triplets that feature virtual replicas of physical spaces. This can significantly enhance the human interaction with these virtual replicas. This allows individuals to not just experience, but also actively manipulate a virtual replica of a physical space.

Users can express actions in detail, including manipulating the position and orientation of an object and applying precise amounts of pressure to specific points on objects.

These virtual interactions can be used to convey ideas, or directly transmitted to robotic devices on-site that execution of changes in the physical environment. This streamlines the communication of complex ideas and instructions through intuitive action.

3.4 Edge Computing

Edge computing moves service provisioning closer to producers and users of such services. It can provide reduced latency, mobility support, and facilitate data analytics to be done close to the data source and creates the possibility for reduced energy consumption.

The convergence of the IoT and edge computing with immersive technologies, such as VR, AR, and MR, is creating a transformative synergy that significantly advances the capabilities and applications of each technology. This integration brings a new era of immersive experiences more interactive, responsive, and integrated with the real world.

The synergies created by IoT, edge computing, AI, and immersive technologies enhanced real-time interactivity and provided low latency by processing data closer to the source. This allows users to experience real-time interaction with virtual environments with minimal delay, making experiences like VR and AR-guided applications more seamless and effective.

With IoT devices generating vast amounts of data, edge computing enables real-time data analytics. This lets immersive applications dynamically adjust content based on immediate user interactions and environmental conditions, enhancing personalisation and responsiveness.

IoT devices and edge computing platforms can provide real-time information about the physical environment, which can be integrated into AR and VR applications to create more contextually aware immersive experiences and improve contextual and spatial awareness.

Spatial computing, IoT, and immersive technologies combine to enable advanced spatial computing capabilities, where the physical and digital spaces are more tightly integrated. Users can interact with digital objects that are aware of and responsive to their environment's physical layout and objects, enabling more natural and intuitive interactions.

IoT devices and edge computing can gather data on user preferences, health metrics, and environmental conditions. This allows immersive applications to tailor experiences in real-time to the individual's needs and context, improving accessibility, personalisation, and user satisfaction.

Wearable IoT devices, edge computing processing, and AI can enhance immersive experiences through biometric data, enabling applications to adjust based on the user's physical responses. This can lead to more engaging and personalised content.

Edge processing reduces the need for constant high-bandwidth connectivity to the cloud, making it more feasible to deploy immersive technologies in bandwidth-constrained environments that increase the scalability and efficiency of the technology. Edge computing can reduce the energy consumption of data processing for IoT devices, extending the battery life of wearable and portable immersive technology devices.

AI can boost IoT and edge computing by offering more intelligent data analysis tools and facilitating real-time autonomous decision-making.

It also foresees maintenance requirements in industrial contexts or tailors' user interactions in virtual settings according to behaviour and preferences. AI's role in comprehending and handling the complexity of interactions within multiverse environments, where several virtual worlds coexist, is essential.

The synergies between IoT, edge computing, and immersive technologies drive significant advances across various sectors by enhancing interactivity, contextual awareness, user experience, and scalability. This integration is paving the way for innovative applications that were previously challenging or impossible to achieve, predicting a new era of digital interaction that muddies the lines between the physical and virtual worlds.

3.5 Spatial Computing

Spatial computing is a foundational technology that enables immersive technologies and bridges the digital and physical worlds. It integrates the understanding and management of physical space into computing, allowing digital objects to exist and interact in three dimensions in a way that mirrors real-life experiences. This capability is central to the development and effectiveness of immersive technologies such as VR, AR, and MR. Here is how spatial computing plays a pivotal role:

Spatial computing enables realistic interactions that allow accurate mapping and understanding of real-world environments and translate that information into digital contexts. This enables immersive technologies to place virtual objects in real spaces so that they appear and behave as if they are truly part of that space.

Spatial computing is used in AR to overlay digital content onto the physical world seamlessly, making it possible for users to interact with virtual objects using their real physical movements.

Spatial computing makes virtual environments more believable and immersive by understanding the spatial relationships between objects and accurately interpreting user movements and interactions. In VR, this means creating a digital space that users can navigate and interact with naturally and intuitively, significantly enhancing the feeling of presence within a virtual environment.

In MR applications, spatial computing is essential for blending real and virtual worlds to enable devices to recognise and react to physical spaces and objects, allowing for the integration of digital content into the physical world at a level of complexity and interactivity previously unattainable. This includes recognising surfaces and boundaries, spatial audio, and interactions that consider the physics of the user's environment.

The role of spatial computing is to allow for a digital access to the real physical world by transforming real objects and assets into situated, digitalized, semantically functional and dynamic digital entities. To accomplish this goal, spatial computing is not limited to geometry reconstruction of the surroundings, but also usually implements a semantic understanding of the scene, using object recognition, segmentation, identification, and state estimation. The result is a complete digital capture of the extent, space, spatial location, functionality, dynamic state of any spatial entity.

Spatial computing enables natural user interfaces (NUIs) that allow users to interact with digital environments instinctively, using gestures, speech, and movement. This removes the need for traditional input devices like keyboard and mouse, making the technology more accessible and engaging for a broader range of users. With spatial computing, designers and developers can create experiences that leverage the three-dimensional space, leading to innovative interaction and engagement.

This includes spatially aware applications and services for education, training, entertainment, and more, offering users novel ways to learn, explore, and connect with content.

Spatial computing technologies, combined with multiple sensors, IoT, edge computing, AI, machine vision, and processing algorithms, allow for precise tracking of user movements and the accurate positioning of virtual objects in real spaces and verses. This precision is vital for applications that require exact interactions and real-time spatial interactions, such as mobile autonomous IoT systems.

The developments and adoption of spatial computing on the web accelerate as web standards evolve and internet speeds increase. The trends are affected by the advancements in industrial-edge immersive technologies that further blur the lines between physical and digital spaces, leading to more innovative applications and changing how we interact with the web and the physical world.

Web 4.0 is envisioned as a more intelligent, autonomous, and decentralised Internet iteration, relying on AI, enhanced data processing, and 3D immersive technologies. Spatial computing extends this vision by adding a layer of spatial intelligence to the Internet, enabling interfaces and experiences that are more intuitive and integrated with the user's physical environment. Integrating spatial computing with IoT means this data can be utilised to create highly contextual and interactive maps of environments. IoT devices can interact with spatial computing systems to create environments that understand and respond to human and machine presence and activities. Edge IoT involves the deployment of numerous sensors and devices that collect data from their environment. Integrating spatial computing with edge IoT and immersive technologies means this data can be utilised to create highly contextual and interactive maps of environments.

Edge computing processes data at or near the source of data generation, which is crucial for spatial computing applications that require low latency, such as autonomous vehicles or interactive immersive applications. It also allows for instantaneous reactions and adjustments in dynamic environments, which is essential for applications like autonomous driving or robotic surgery. Edge AI and machine learning can analyse and learn from the spatial data collected, enhancing the capabilities of spatial computing applications. Based on the flow of people or goods, they can predict patterns and suggest optimisations for spatial layouts in industries like retail or manufacturing. They can also improve gesture and voice recognition systems that interact with spatial computing environments, making them more intuitive and responsive.

Immersive technologies are natural extensions of spatial computing, providing users with immersive experiences that blend real and virtual worlds and enhance the realism of virtual environments by accurately replicating the physics and geometry of real-world spaces and enabling a shared virtual workspace where physical boundaries are no longer a limitation, allowing real-time collaboration and interaction.

Integrating spatial computing with Web 4.0, IoT, edge computing, AI, and immersive technologies could lead to a more intuitive, efficient, and interactive digital future. This convergence promises to reshape how we interact with digital systems and the physical world, making our interactions more synchronised and context-aware.

Spatial computing provides the technical underpinning for immersive technologies to flourish, and for AR, VR, MR to be integrated in an XR unified approach offering tools and frameworks that bring digital and physical realms closer together. As spatial computing evolves, it will continue to expand the capabilities and applications of immersive technologies, making them more integrated into daily lives and work.

3.6 Edge Artificial Intelligence

AI creates inclusive interfaces that will make the users' journeys convenient for everyone, including people with disabilities (e.g., improve implementation of universal design). Thus, AI makes the immersive applications user-friendly and easy-to-use platforms. Technologies such as NLP, speech recognition, computer vision, translation, and AR enable users to interact with the metaverse in their native language through images and videos and enhance user-verse interactions.

Integrating edge AI with immersive technologies like VR, AR, MR, and verses (e.g., metaverse, omniverse, multiverse) fosters a new wave of innovation and enhanced capabilities. This synergy improves immersive applications' performance and user experience and opens new possibilities for use in various fields.

Real-time and pseudo-real-time processing, decision-making and responsiveness combined with analytics performed by edge AI models and algorithms means user actions can be processed and reflected in the virtual environment almost instantaneously. This is crucial for maintaining immersion and preventing motion sickness in VR applications. It allows for immediate recognition and overlay of digital information on real-world objects, enhancing user interaction with their environment.

Edge AI and generative AI can improve dynamic content adjustment by leveraging AI models that run on the edge; immersive applications can dynamically adjust content based on the user's behaviour, preferences, and immediate environment, and an AR-based learning application can modify its teaching methods in real-time based on the learner's engagement level and understanding.

Edge AI can process data from various sensors embedded in the environment or the device to better understand the context, the environment and the spatial location and adapt the immersive experience accordingly.

This is particularly useful in AR applications for indoor and outdoor navigation and interactive autonomous systems, robotics, and human interaction, where the digital content and the immersive triplets need to be aware of the physical space.

AI, ML, and computer vision algorithms integrated at the edge enhance immersive technologies' capabilities. Gesture recognition and object detection can be performed locally on AR glasses, enabling more natural interactions with digital content without needing external HW.

In this context, edge AI plays a crucial role in spatial computing, where the technology understands and interacts with the physical space around it. This is fundamental for creating coherent and interactive AR and MR experiences seamlessly blending digital content with the real world. In addition, edge AI can be used for proper and adequate identification of objects function, position, dynamic state and thus allows for enhanced interaction possibilities with real world through digitalisation.

Edge AI can directly implement real-time security measures, such as anomaly detection and immediate response to potential threats, on the device. This adds an extra layer of security for immersive applications that may be processing sensitive information.

While integrating edge AI with immersive technologies offers numerous benefits, it also presents challenges, such as the need for advanced hardware that supports AI computations, the complexity of developing and deploying AI models on edge and ensuring the interoperability of devices and platforms. Addressing these challenges requires ongoing technological advancements, standardisation efforts, and a focus on developing lightweight AI models that can run efficiently on edge devices.

Next to the development of lightweight, classical AI models, neuromorphic and event-based AI models can also address the challenges faced by edge AI implementations. These approaches are biologically inspired and research novel neuron models. By exploiting sparsity in the sensor data and the computations of the resulting AI model, these AI systems can run with less energy and memory requirements but face new training challenges.

The synergy between edge AI and immersive technologies significantly enhances the capabilities, performance, and applications of VR, AR, MR, and immersive verses (e.g., metaverse, omniverse, multiverse). By enabling real-time processing, personalized experiences, and advanced interactive features, this integration is paving the way for the next generation of edge IoT immersive applications across various sectors.

3.7 Spatial Generative Edge Artificial Intelligence Technologies

As technology advances, the AI-generated content is making its way into edge immersive technologies through AI-powered algorithms, and the ability to understand and respond to context combined with the capabilities to generate coherent, relevant, and appropriate scenarios and novel situations.

Generative AI technologies can generate text and audio descriptions of the virtual spatial environments, which can help make the experience more immersive and engaging for human and machine users combined with generated interactive dialogue for virtual characters that users might encounter on the virtual world.

Heuristics, as a methodology, facilitate immersive systems' abilities to solve problems using practical and intuitive methods. Generative heuristics can employ rules of thumb, educated guesses, and simplified strategies to approximate solutions, particularly in complex and non-deterministic situations.

Heuristics steer the search for solutions in areas where exhaustive exploration is impractical or impossible, thus aiding in the discovery of acceptable solutions within a reasonable timeframe.

One major challenge is ensuring that the AI-generated content in immersive applications is accurate and relevant as generative AI models are trained on a large dataset of text, images, videos. This may create problems to generate content that is entirely accurate or relevant to a specific edge location, context or scenario and may not always be able to create appropriate content for all users, which can lead to issues with accessibility.

Immersive technologies require the use of multimodal generative AI technologies trained on different types of media, like text, images, voices, audio, and videos and capture multi-lingual elements.

Combining AI-generated content in immersive environments raises certain ethical questions. As generative AI technologies are based on an autonomous system, and it can generate text, images, videos, voices based on what it has learned from the data it was trained on, which could include biases and stereotypes. This requires continuous monitor and review of the generated content to avoid any unwanted biases or stereotypes.

Spatial generative edge AI technologies represent a cutting-edge fusion of spatial computing, generative AI models, IoT and edge computing, explicitly tailored for immersive technologies like VR, AR, MR, and verses (e.g., metaverse, omniverse, multiverse). This integration aims to enhance the creation, interaction, and personalisation of digital content within physical spaces in real-time, leveraging the power of AI directly on edge devices.

Understanding spatial generative edge AI involves using spatial computing to provide edge IoT devices with the ability to understand and interact with their physical environment in three dimensions.

In immersive technologies, spatial computing enables devices to map environments, recognise objects and spaces, and place digital content in the physical world so that it appears to coexist with real-world objects.

Generative AI models can create new data that resembles the training data and create new scenarios, sceneries, and simulation environments. Applied to immersive technologies, these models can generate realistic textures, objects, or entire environments on the fly, enhancing the richness and diversity of immersive experiences. By processing data on local devices or nearby computing resources, edge computing reduces latency, conserves bandwidth, and improves privacy. This is crucial for immersive technologies that require real-time processing to maintain immersion and user engagement.

Spatial generative edge AI can dynamically generate content based on the user's environment and interactions. The environment could adapt in real-time to the physical space around the user, generating obstacles or items based on the space's layout.

For immersive AR environments, spatial generative AI can be used to seamlessly fuse the real surroundings with generated virtual objects and entities, leading to hyper realistic fusion of virtual and real. With generative AI, photorealistic rendering of extended reality is possible, lowering the acceptance barrier of augmented and mixed reality for the user.

The technology can generate realistic scenarios and environments for training and simulation applications that adapt to the user's actions and decisions, providing a highly personalised and practical learning experience.

Spatial generative edge AI can personalise immersive experiences in real-time by understanding the user's preferences and environment context. This could range from adjusting the difficulty level of a simulation to changing the ambience of a virtual meeting space based on the participants' preferences.

In the same manner, interactive immersive triplets and avatars can be created in different contexts, spaces, and time dimensions. Users can interact with these interactive immersive triplets and avatars through VR, AR, MR, and verses (e.g., metaverse, omniverse, multiverse), enabling them to visualise data, simulate changes, and understand complex systems intuitively.

Running sophisticated spatial generative edge AI models requires energy-efficient and performant HW that can handle intensive computations while maintaining low energy consumption, which can be challenging for portable and wearable devices. To address this challenge, edge AI models, especially generative ones, must be highly optimised for edge deployment to ensure they operate efficiently in real-time without compromising the quality of the generated content.

Ensuring seamless interaction between different edge immersive IoT devices, platforms, and data formats is crucial for the widespread adoption of these technologies, requiring ongoing standardisation and development efforts to provide interoperability and scalability.

Spatial generative edge AI technologies are poised to revolutionise immersive experiences. By leveraging the synergy between spatial computing, generative AI, and edge computing, they will offer unprecedented levels of personalisation, realism, and interactivity. As these technologies evolve, they will unlock new possibilities for creating immersive, intelligent, and trustworthy environments that seamlessly integrate with the physical world.

3.8 Immersive Intelligent Mesh Connectivity

Immersive technologies are all about connecting virtual experiences, and networking with immersive spaces can use enormous amounts of data. Intelligent wireless and cellular connectivity technologies provide the increased bandwidth and power needed for real-time data transfers. Wireless and cellular technologies enable people and machine to connect to immersive experiences from anywhere in real-time. The immersive technologies extended to verses is not just about one person and one machine but about a mesh of devices that exchange enormous amounts of information in real-time in physical, digital, virtual, cyber, and spatial environments.

Edge immersive technologies create environments in which users move seamlessly between real and virtual worlds. This can create new communication experiences that engage parties from various remote locations. Immersive technologies are virtually freeing users from physical constraints, transcending space, and time, and bringing about the advent of a society where users can create the environments they like according to their diverse values.

To realise the intelligent communications supporting such virtual environments, data from diverse phenomena, life activities, and meaningful contextual and emotional states must be collected and shared while ensuring users' privacy. Beyond simply increasing communications performance, this requires real-time analysis, archiving, and utilising the tremendous amounts of data generated by the real world.

In this context, the intelligent wireless and cellular 5G/6G and beyond offer next-generation systems integrating communications infrastructure with high capacity, low latency, massive connectivity, embedded intelligence and sustainability with technologies and products that use real-time processing of immense amounts of diverse data wherever they are located.

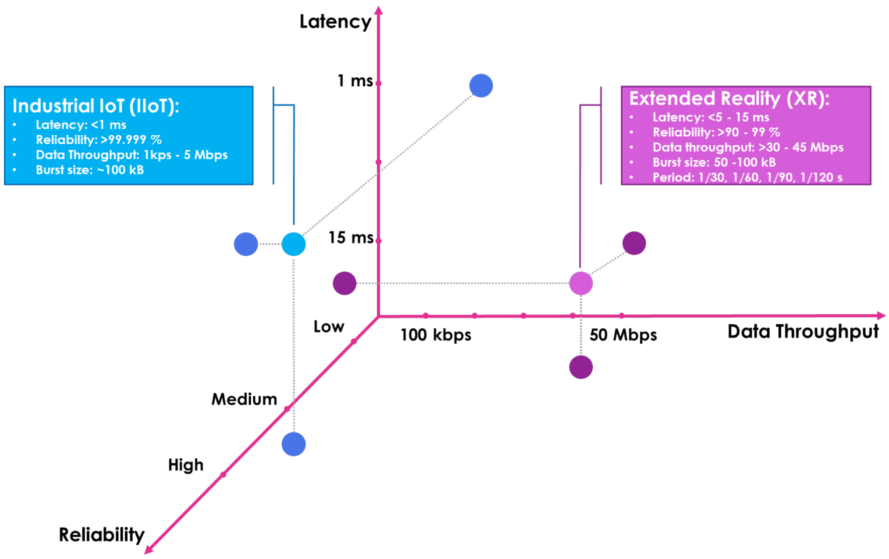

Figure 4-4 IIoT and XR traffic characteristics. Source: Adapted from Nokia.

The Figure 4-4 illustrates the traffic characteristics (latency, data throughput and reliability) of IIoT and XR applications, highlighting the high data throughput required to simultaneously transmit 3D video streams and data control over the same end-to-end communication channel.

Latency, reliability, and data influence the communication network design from edge IoT devices, architecture, traffic management perspective and the total processing time along the delivery chain (wireless components, codecs, queues, etc.). This is increased with additional sensory communication.

Latency is critical in acquiring an immersive experience since human perception requires accurate and smooth movements in vision. Increased latency can lead to a detached immersive experience and contributes to the sensation of motion sickness.

XR applications shift to more natural forms of communication between humans and machines, with a potential for greater intelligence on the machine side and edge IoT devices.

The bit rate can be calculated by the image sampling rate in time (smoothness), space (details), chromaticity (colour) and sensation of depth. The raw bit rate is based on the number of pixels per minute arc angle, chroma sampling, the number of bits representing each pixel and frame rate. The calculated raw bit rate is based on 2 pixels per minute arc (Nyquist), 4:4:4 chroma sampling, 10-bit colour space (YCbCr), 120 frames per second and two images for right and left eyes. For example, a raw bit rate of 2.45 Tbps has been calculated to encode a 360 spherical video that achieves the ultimate immersive experience [56].

With intelligent connectivity IoT Senses, remote rendering, generative AI are part of the experience spaces. Intelligent connectivity reduces latency, the time data transfers between the source and its destination. Latency directly affects the frames per second (FPS) that can be streamed to a headset. Next-generation wireless and cellular intelligent connectivity may reduce the latency below 10 ms and close to 1 ms, and the virtual rendered objects frame rate reaches 90 FPS, enabling remote rendering.

XR represents the convergence of physical and virtual experiences that create an immersive environment. XR technologies, including AR, VR, and MR, extend reality by merging virtual effects with real-world applications to enhance or simulate real-life scenarios. With high levels of interactivity and immersion, XR delivers engaging, untethered virtual experiences to online users. Delivering XR experiences involves different data flows within a single edge device, such as video, audio, haptic, and sensor data. Securing these data streams simultaneously to enhance the immersive experience is a challenge related to QoS policy coordination, policy control for application synchronisation, and interaction for seamless coordination.

Achieving synchronisation and QoS policy coordination is paramount for multi-modal communication sessions across multiple edge devices. This challenge involves delivering related tactile and multi-modal data (e.g., audio, video, haptic) to users at identical times. The Table 4-2 presents the QoS requirements that must be fulfilled to meet the users' quality of experience (QoE) [1].

Table 4-2 QoS requirements for multi-modal streams [1].

	Haptics	Video	Audio
Jitter (ms)	≤2	≤30	≤30
Delay (ms)	≤50	≤400	≤150
Packet loss (%)	≤10	≤1	≤1
Update rate (Hz)	≥ 1000	≥ 30	≥ 50
Packet size (bytes)	64 - 128	≤ MTU	160 - 320
Throughput (kbit/s)	512 - 1024	2500 - 40000	64 - 128

Immersive technologies require localised information for spatial mapping and localisation service enablers, addressing the evolution towards joint sensing and communication systems. Localisation involves continuously tracking objects to determine their precise location and orientation over time.

Service providers must deliver and utilise spatial map information in the localised mobile immersive use cases. This results in creating dynamic 3D maps for indoor and outdoor environments. This dynamic use case underscores the primary significance of spatial mapping and localisation as catalysts for diverse services.

The immersive applications use different edge devices, including wearables (e.g., smart watches, wearable medical devices, AR/VR goggles, etc.), industrial wireless sensors, and video surveillance. These edge devices put some generic requirements on the system, such as reduced device complexity, compact form factor, etc. as presented in Table 4-3.

Table 4-3 Requirements of wearables, industrial wireless sensors, and video surveillance use cases [1].

	Data rate	Latency	Availability/Reliability	Battery lifetime	Device size
Wearables	5 - 50Mbps DL, 2 - 5 Mbps UL	Relaxed	N/A	Up to 1-2 weeks	Compact form factor
Industrial Wireless Sensors	< 2 Mbps	< 100 ms	99.99%	At least a few years	N/A
Video surveillance	2-4 Mbps for economic video, 7.5-25 Mbps for high-end video	< 500 ms	99%-99.9%	N/A	N/A

Immersive intelligent mesh connectivity represents a concept that merges several cutting-edge technologies to create highly adaptable, efficient, and immersive network infrastructures that conceptually integrate aspects of immersive technologies (VR, AR, and MR), intelligent systems (AI and ML), and wireless mesh networking to provide seamless, dynamic, and context-aware connectivity solutions.

Incorporating AI and ML into network and application infrastructures allows for the analysis of vast amounts of data in real-time, enabling adaptive and predictive functionalities. These systems can optimise network performance, anticipate user needs, and provide personalised content or recommendations, enhancing user experiences and operational efficiency in various immersive applications.

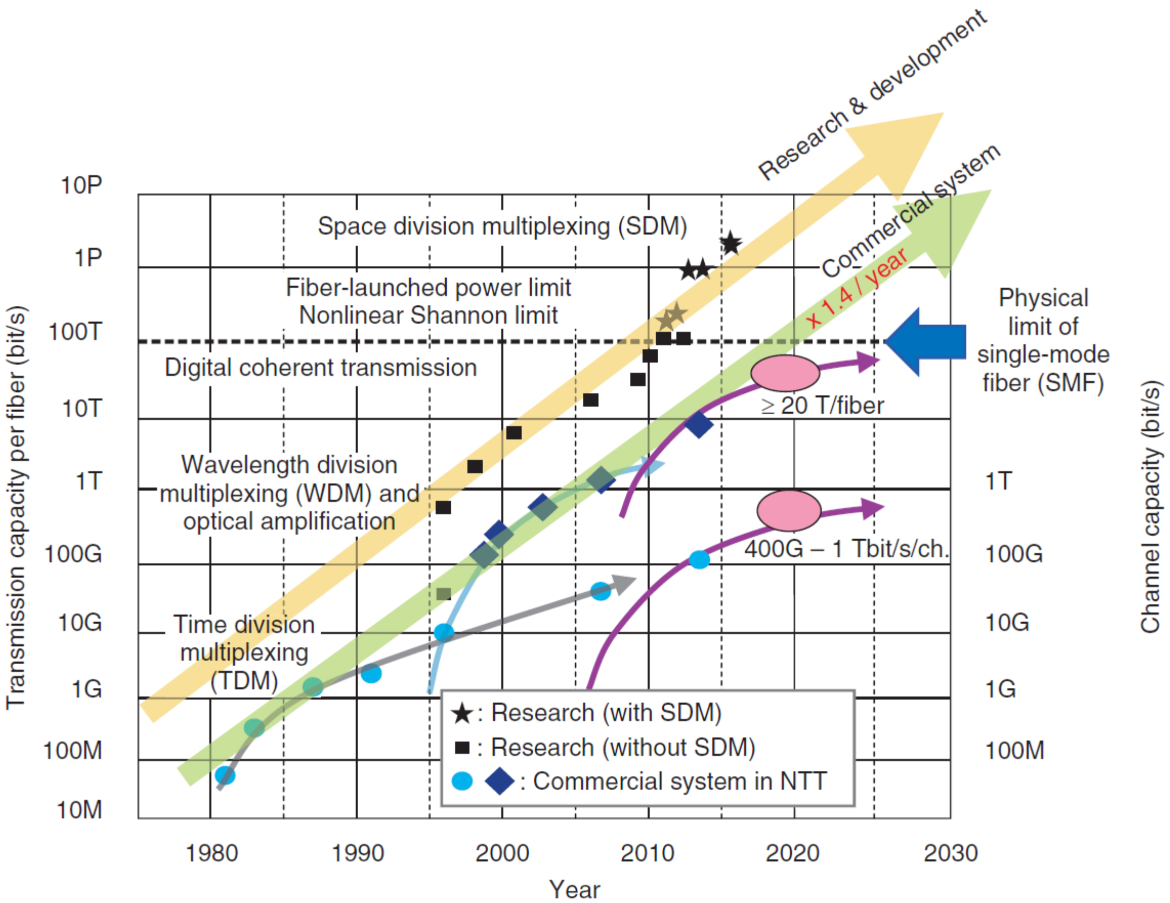

Figure 4-5 The evolution of high-capacity optical fibre transport networks. Source: [60].

The total fibre optical spectrum available is more than 1000 THz, and core networks that will provide connectivity capacity for immersive applications rely almost entirely on fibres.

The Figure 4-5 shows the evolution of high-capacity optical transport fibre networks and the leading technologies that have impacted the evolution. The limits of optical fibre technology are comparable to Moore's Law, which shows the exponential growth in the number of devices in semiconductor circuits and of similar log gradients growing by a factor of 1.4 per year [60].

Mesh networking involves a network topology where nodes connect directly, dynamically, and non-hierarchically to as many other nodes as possible and cooperate to efficiently route data to and from users in real and virtual environments. This self-healing, flexible networking approach ensures high reliability and scalability. Immersive intelligent mesh connectivity enhances immersive experiences by facilitating high-bandwidth, low-latency connections essential for VR, AR, and MR applications. It ensures users relish seamless, realistic, immersive experiences without interruptions or delays.

Technologies convergence leverages AI for optimisation and personalisation to manage network resources dynamically, adapting to user behaviour and environmental changes to optimise performance and enhance user experiences in real and immersive environments. This includes AI-driven content delivery, network security, and user interface adaptation.

The immersive technologies employ the mesh network infrastructure to provide robust, extensive coverage to ensure users can access immersive, intelligent services anytime, anywhere, to any device by creating flexible, efficient workspaces that rely on a mix of real and virtual interactions. The integration of these technologies could provide the next-generation digital infrastructure, offering unprecedented levels of integration, interaction, and immersion in digital environments.

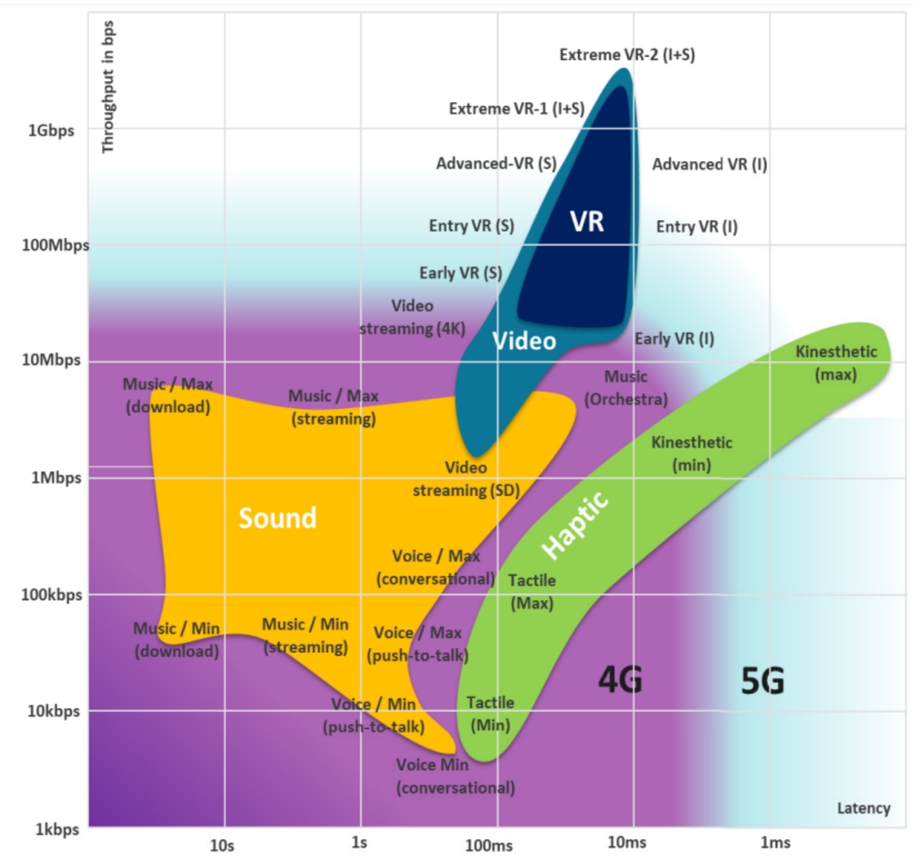

Figure 4-6 Sensory communications throughput and latency requirements. Source: [43].

The advancement, development, and roll-out of intelligent connectivity technologies and networks are critical as immersive technologies require ubiquitous communication and real-time interaction. The throughput and latency requirements for different components of the immersive technologies landscape are illustrated in Figure 4-6, which clearly show that VR requires significantly higher throughput and lower latency than video applications. As a result, the degree to which immersive technologies can achieve full immersion and broad accessibility hinges on deploying and adopting connectivity options like optical fibre, 5G, Wi-Fi 7, and forthcoming technologies such as 6G.

Immersive experiences require stringent low latency and high bandwidth performance to deliver immersive environments and real-time behaviour. The capabilities of new Wi-Fi protocols enable the full potential of immersive applications, supporting responsive, engaging AR, VR, MR, XR and verses experiences by providing multi-gigabit speeds for instantaneous data exchange, power efficiency to deliver rapid, efficient data transfers and bounded latency and high reliability for lag-free experiences in congested environments.

Wi-Fi serves as one of the foundations of connectivity for new and emerging immersive applications. The 6 GHz spectrum of Wi-Fi 6E and Wi-Fi 7 ensures that edge devices delivering immersive experiences meet the high standards for QoS and QoE performance, interoperability, and security.

Wireless and cellular 5G/6G and beyond technologies are the ones offering the high-bandwidth, low-latency communication necessary to support seamless interactions between physical, digital, and virtual spaces.

To further boost XR performance, 5GAdvanced (starting with 3GPP Rel-18 - Table I-1) introduces several heterogeneous enhancements and activities handled within various 3GPP Service and Systems Aspects (SA) and Radio Access Networks (RAN) group, including both XR-specific enablers and service-agnostic enhancements. An overview of these innovations is illustrated in Figure 4-7.

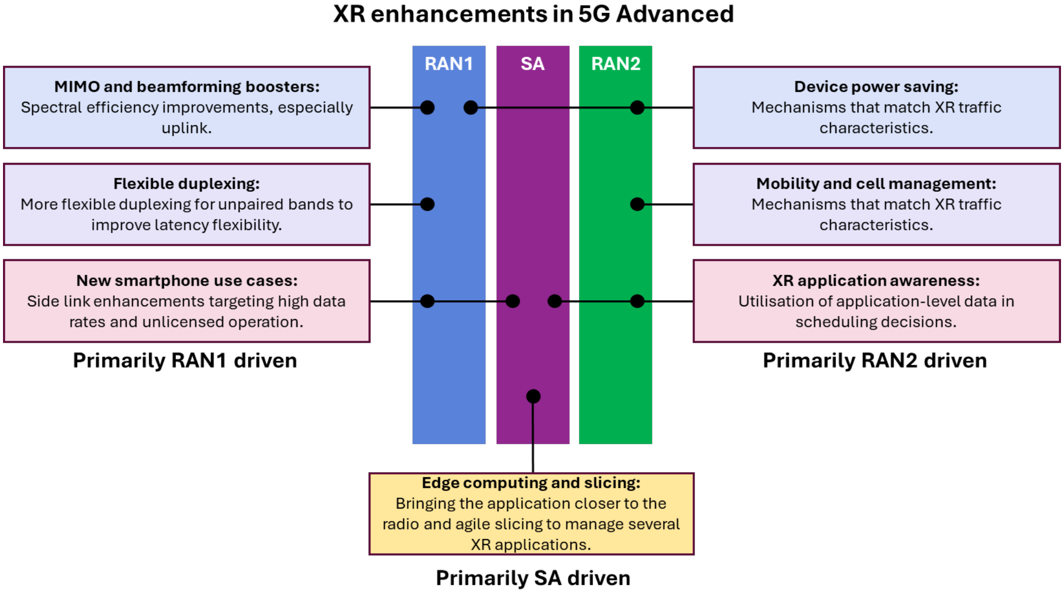

Figure 4-7 Improving support for the XR in 5G-Advanced. Source: Adapted from [34].

The 3C connected collaborative computing merges the IoT, network technologies, edge computing, AI infrastructure and platforms and integrate them into different applications across industrial sectors.

The 3C ecosystem, which spans semiconductors, IoT, platforms, AI, computational capacity at edge and cloud environments, communication technologies, connectivity infrastructure, data management, and applications are essential for large-scale pilots that set up end-to-end integrated infrastructures and platforms and bring together players from different segments of the connectivity value chain and beyond to demonstrate the convergence of technologies in different industrial sectors.

Some applications will need data from IoT located in areas not covered by wireless or mobile/cellular networks, and 6G will integrate satellite connectivity to address these specific cases. With such integration, the ATAWAD (**A**nyTime, **A**nyWhere **A**nyDevice**/A**nything) value proposition will be reached, and immersive applications will take advantage of that evolution.

3.8 Integration of Sensing and Communications

Integrating advanced IoT sensory technologies and intelligent mesh connectivity is essential for converging edge immersive technologies. Edge AI and immersive intelligent mesh connectivity allow for the classification, detection, localisation, and estimation of an object's attributes and other functions. The IoT is expected to combine sensing and communication technologies into a fully integrated system. Systems incorporating joint communication and sensing (JCAS) functionalities represent a significant innovation for 6G that will facilitate numerous emerging immersive technologies and applications and enable the concept of a perceptive network.

The communication component of an JCAS system would mean connecting the digital, physical, and human worlds in real-time with all extreme requirements coming from the immersive technology value chain (Figure 4-1). The sensing component, on the other hand, will provide us with the capability to sense the world and to provide context information to create the digital map of the environment, which is a prerequisite for creating the DTs and seamless integration of the physical, digital, virtual, and cyber worlds. With JCAS in 6G and beyond, we will have the capability to not only localise objects that are part of the network but also to sense and integrate objects that are not connected to the network. For real-time immersive applications, integrating a human model with a DT representation of the physical world entails exchanging multimodal data, such as haptics, position, velocity, and interactions, as well as the senses in the IoT context, including human gestures, head movements and posture, eye contact, facial expressions, emotions, etc. [44].

The JCAS integration is envisioned in different ways, from loosely coupled to fully integrated, shared spectrum, shared HW, to shared signal processing module and network protocol stacks, and even using the same waveform for both communications and sensing. Sensing functionality can be introduced as a service with a low incremental cost as it leverages equipment and spectrum deployed for communication purposes. JCAS can extend the capability of cellular networks by adding see-and-feel functionalities. The edge devices can sense their surroundings and exchange their sensing results through communication links. From a network perspective, the widely deployed base stations for legacy cellular service could be re-used for wide-area seamless RF sensing. Incorporating AI, communications, positioning, and sensing capabilities, the cellular network could intelligently fuse the physical world with the digital world and provide various new services for consumers and industry customers [1].

Systems with JCAS functionalities are still in their early stages, and during the next few years, a substantial amount of additional research will be needed. They will also share resources in the time, frequency, and space domains and essential components, including HW, waveforms, and signal processing. This implies that the signals of the cellular system will be used to significantly increase the sensing capabilities in addition to the communication network transporting sensor data.

Integrating communication and sensing can add ambient IoT to budget-friendly and power-efficient edge devices that facilitate the connection of numerous objects and items to networks, allowing for many applications. The driving forces behind ambient IoT are energy harvesting, storage, and backscattering techniques. Energy harvesting and storage can include diverse energy sources, including RF signals, light, vibrations, and thermal energy. Different energy sources have varying levels of availability and energy density. The backscattering technique can involve a few other factors. Backscattering, combined with active signal generation (e.g., power amplifiers), minimises power consumption in Ambient IoT devices. In backscattering, the transmitted signal reflects continuous waves from a reader, modulated with information for communication. Ambient IoT's reliance on energy harvesting and backscattering holds the potential to advance low-cost, maintenance-free, and environmentally sustainable IoT solutions.

The combined functionality of communication and sensing also facilitates emerging secure proximity services. Such technology ensures the secure and private exchange of data between devices in close physical proximity, enabling applications like mobile payment, intelligent access control, communication to everything and IIoT. The sensing feature acts as the authentication mechanisms to safeguard the communication and prevent unauthorized access or data breaches. JCAS also allows secure communication links by localising potential eavesdroppers, preventing the decoding of malicious data, and activating focussed counter-attack measures based on encryption and authentication protocols in combination with dynamic beamforming or special filtering.

The ambient IoT edge devices can be used as part of the immersive spaces to provide real-time information about the environmental conditions in the physical world.

5. Immersive Physical-Digital-Virtual Spatial Computing Continuum

The immersive physical, digital, virtual, and spatial computing continuum refers to the seamless integration and interaction across physical, digital, and virtual environments facilitated by advanced computing covering edge, swarm, spatial, fog and cloud technologies. This continuum is built on the foundation of processing data and providing capabilities to enable computers to understand and manipulate spatial data representing the physical world and its dynamics in digital, virtual and 3D spatial forms.

The key elements of this continuum include the physical, digital, virtual and 3D spatial spaces. The physical space is defined by the tangible, real-world environment, which includes everything from the physical layout of a room to the natural environment outside. Spatial computing technologies in this domain often involve sensing and affect physical space, such as robotics and IoTS devices.

The digital space is defined by the digital representation of information, including the physical world's digital twins and purely digital data and processes. This space is where data from the physical world is collected, processed, and analysed to create actionable insights or simulations. The virtual space encompasses fully digital environments that can be experienced with high degree of immersion through technologies like VR, AR, and MR. These spaces are not bound by the physical laws of the real world, allowing for experiences considerably different from real-life interactions.

The continuum emphasises the fluid movement and interaction between these spaces, providing a comprehensive framework for understanding how digital information and virtual experiences are increasingly integrated into our physical world.

Spatial computing supports 3D space and refers to the computational techniques and technologies that enable the above interactions, including computer vision, sensor fusion, and spatial reasoning, allowing computers to perceive and interact with the 3D world.

The immersive physical, digital, virtual, and spatial computing continuum represents an emerging vision where the boundaries between these spaces become increasingly blurred, enabling more natural and intuitive interactions with and through technology. This continuum is about the technologies and creating experiences that enhance human and machine capabilities, improve efficiency, and enable new forms of creativity and expression in immersive applications.

The convergence and synergies between immersive technologies (VR, AR, and MR) and holographic technologies represent a significant evolution in how we interact with digital information and the physical world. This convergence creates new possibilities for interaction, visualisation, and communication, blending the physical and digital realms.

Integrating holographic displays with VR and AR technologies can enhance the sense of immersion and realism. Holograms can be projected into the physical space, allowing users to view and interact with 3D images without needing headsets or specific viewing angles. This integration can make virtual meetings, telepresence, and remote collaboration more lifelike and engaging.

By combining holographic technology with spatial computing and gesture recognition, users can interact with holograms directly without wearables. This synergy allows for creating interfaces and applications where information can be manipulated with hands or body movements, eliminating the need for controllers or wearable devices.

Alternatively, using controllers or wearables that can provide additional forms of feedback, such as vibrotactile, resistive, and active force feedback, allows the user to have a richer experience of the digital environment or virtual replica. These additions could enable humans to express actions in greater detail, including the amount of applied pressure required to handle tasks that require great precision and subtlety. These additions can also be used in applications where vision alone does not provide sufficient information, for example, due to an obstructed view.

Edge immersive technologies require participants to use their devices (like VR headsets) to experience digital content. The integration with holographic technology enables multiple users to view and interact with the same digital content simultaneously in a shared physical space, fostering collaboration and making shared experiences more natural and accessible.

Current AR technology overlays digital content onto the real world through screens or AR glasses, which can sometimes lack depth and spatial accuracy. Holographic technology can provide better depth cues and spatial positioning, making digital content appear as though it is genuinely part of the physical world.

The convergence of immersive and holographic technologies has several challenges, including hardware limitations, cost, and the need to develop holographic display technologies further. As these technologies advance, they promise to create more natural, intuitive, and accessible ways to interact with digital content, leading to innovations that could reshape edge immersive applications where digital and physical realities are seamlessly blended, offering enriched, interactive, and accessible experiences.

6. Industrial Immersive Systems of Systems Integration

Integrating industrial immersive systems with IoT, edge computing, AI, and industrial immersive technologies, such as VR, AR, MR and verses (e.g., metaverse, omniverse, multiverse) and Web 4.0 technologies presents a transformative opportunity for industries, enabling more efficient operations, enhanced decision-making, and immersive, interactive experiences. The integration of these advanced technologies into cohesive systems of systems (SoS) faces several significant challenges:

Interoperability and Standardisation

Challenge: Different devices and systems often use proprietary protocols and data formats, making seamless communication and data exchange difficult. This lack of interoperability can hinder the integration process and limit the potential benefits of a fully connected ecosystem.

Impact: Without standardisation, industries may face increased costs and complexity in integrating disparate systems, potentially leading to siloed information, and reduced operational efficiency.

Scalability and Flexibility

Challenge: As the number of connected devices grows, the system must scale without significant performance losses. Additionally, the system needs the flexibility to integrate new technologies and adapt to changing operational requirements.

Impact: Failure to address scalability and flexibility can result in inefficiencies or costly upgrades.

Trust, Data Privacy and Security

Challenge: Integrating IoT, edge computing, and AI increases the amount of data collected, processed, and stored, raising significant data privacy and security concerns. Protecting this data against unauthorised access and ensuring compliance with regulations such as GDPR becomes more complex in a highly interconnected environment.

Impact: Breaches or non-compliance can result in significant financial penalties, loss of customer trust, and damage to the company's reputation.

Real-time Data Processing and Decision Making

Challenge: Industrial immersive systems often require real-time or near-real-time data processing and decision-making capabilities. Achieving this level of performance, especially in complex environments with high data volumes, is challenging.

Impact: Delays in data processing or decision-making can lead to missed opportunities for optimisation, reduced operational efficiency, and potentially unsafe conditions in critical industrial processes.

IoT, Edge Computing and AI Infrastructure

Challenge: Implementing edge computing infrastructure requires significant investment in HW, SW, and interoperable platforms. Additionally, managing and maintaining this infrastructure, especially across distributed locations, can be complex and resource-intensive.

Impact: With adequate investment and management, the benefits of edge computing, such as reduced latency and improved data privacy, may be fully realised, impacting the overall effectiveness of the integrated system.

AI Model Accuracy and Trustworthiness

Challenge: Developing robust and bias-free AI models is difficult, especially when dealing with complex, real-world data. Ensuring these models can operate effectively ethically, and safely (without causing any harms to human) in an industrial context is a significant challenge.

Impact: Inaccurate or biased AI models can lead to incorrect decisions, inefficiencies, and potential harm, undermining trust in the system and limiting its effectiveness.

User Acceptance, Adoption and Training

Challenge: The success of integrated systems also depends on user acceptance and the availability of training. Users need to trust the technology and understand how to interact effectively.

Impact: User resistance or a lack of proper training can hinder the adoption and effective use of integrated systems, reducing their potential benefits.

The integration of IoT, edge computing, and AI into industrial immersive systems of systems presents a promising future for industries. Overcoming challenges related to interoperability, scalability, privacy, real-time processing, infrastructure, AI accuracy, and user acceptance is crucial for realising the full potential of these technologies. Addressing these challenges requires a collaborative effort among technology providers, industry stakeholders, and regulatory bodies to develop standards, best practices, and innovative solutions that pave the way for successful integration and adoption.

7. Industrial Immersive Trustworthiness

Creating a trustworthy framework for IoT, edge computing, AI, and industrial immersive technologies, such as VR, AR, MR and verses (e.g., metaverse, omniverse, multiverse), requires a comprehensive approach integrating system engineering dependability principles. Dependability in this context encompasses attributes such as availability, reliability, safety, integrity, and maintainability, which are critical for industrial applications where errors or downtimes can lead to significant risks or losses. These principles can be applied to build a trustworthy framework for industrial immersive technologies by considering system properties implemented for specific immersive technologies and applications.

Availability requires implementing industrial immersive redundant solutions with redundant HW and SW systems to ensure that if one component fails, another can take over without disrupting the immersive experience. This is crucial in industrial settings where downtime can be costly. This implies a robust network infrastructure that ensures a robust, reliable, intelligent connectivity that can support immersive applications seamless and continuous operation, including provisions for network failures.

Reliability requires fault tolerance to be embedded in the immersive system design, allowing the system to continue operation even in the presence of faults. This includes error detection and correction mechanisms that can identify and mitigate issues without interrupting the user experience. This implies the use of mechanisms for a structured automated upgradability and updatability approach, allowing regular SW/firmware/algorithms updates and patches to address vulnerabilities and bugs and improve system performance, ensuring the reliability of the immersive technology, but also a substantial improvement of the current sensing technologies being more accurate, reliable, cost worthy in error detection.

Safety requires continuous risk assessment and mitigation to identify potential safety hazards when using immersive technologies in industrial environments. To address these risks, it is critical to develop and implement mitigation strategies and provide comprehensive user training and clear guidelines on the safe use of immersive technologies, including measures to prevent physical and psychological harm.

Security and data integrity require data encryption and security protocols to protect sensitive information transmitted or stored by immersive systems, ensuring data integrity and confidentiality. Authentication and access control mechanisms are vital in industrial-edge immersive technologies to prevent unauthorised access to immersive systems, ensuring that only authorised personnel can use or modify the system.

Maintainability requires using modular design approaches that allow for easy replacement or upgrading of components without affecting the overall system operation. This facilitates quicker repairs and updates, enhancing system maintainability. As immersive technologies operate online and interact with each other remotely and via the Internet, remote diagnostics and support capabilities are mandatory to enable timely identification and resolution of issues, minimising the need for on-site maintenance and reducing downtime.

Usability is based on the user-centred design principle to ensure that immersive technologies' design focuses on user needs and ergonomics, making systems intuitive and straightforward to use, which is essential for adoption and effectiveness in industrial settings. This approach requires the implementation of feedback mechanisms or collecting user feedback on the system's performance and usability, allowing for continuous improvement based on real-world use.

Ethical considerations related to privacy protection must be enforced by implementing measures to protect personal and sensitive data collected or used by immersive technologies.

This has to be combined with practices that include transparency and accountability about immersive technologies' capabilities, limitations, and use of data, ensuring accountability for their performance and impact.

Creating a trustworthy framework for industrial immersive technologies involves a holistic approach that integrates system engineering dependability principles with considerations for usability, including explainability and interpretability mechanisms for AI-based models, ethical issues, and the specific needs of industrial environments. By addressing these aspects, organisations can develop and deploy immersive technologies that are effective, engaging, reliable, safe, and trustworthy.

8. Immersive Technologies Standardisation

Immersive technologies are not developed in isolation but as part of a complex ecosystem integrating multiple stakeholders, disciplines, and standards covering devices, infrastructure, core technologies, platforms, and services as illustrated in Figure 8-1.

This requires an approach to standardisation combining standards for different specific technologies, standards for industrial applications, and standards for the disciplines and industrial sectors.

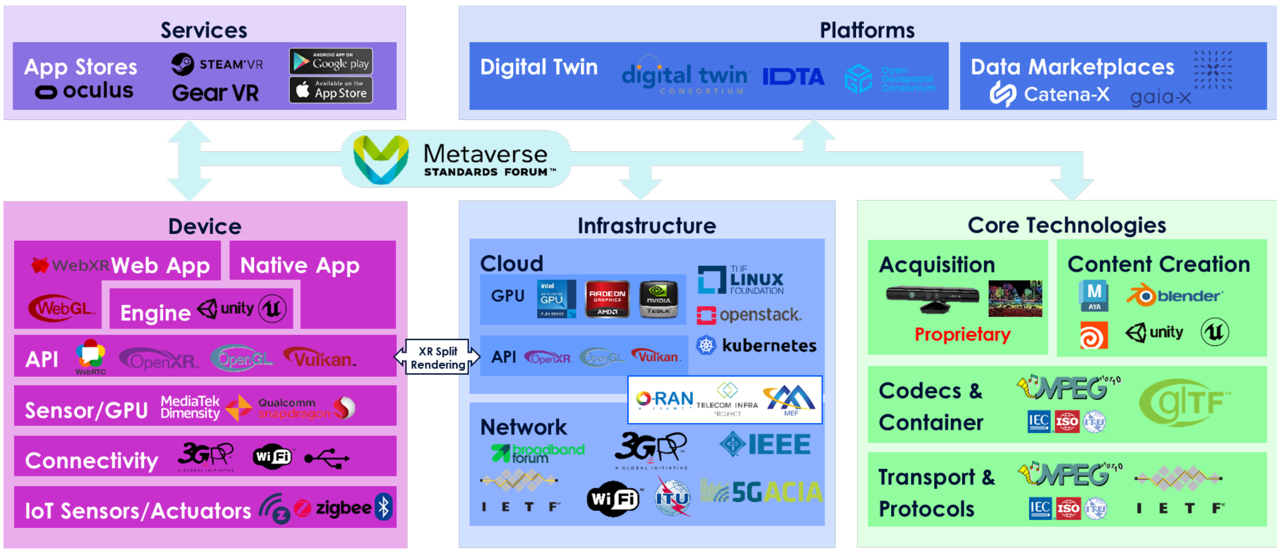

Figure 8-1 Edge immersive technologies ecosystem. Source: Nokia.

Immersive technology standards are guidelines and specifications that ensure interoperability and quality in VR, AR, XR, verses and Web 4.0 technologies. These standards are developed by standardisation organisations (SDOs) such as the 3rd Generation Partnership Project (3GPP), the British Standards Institution (BSI), the Institute of Electrical and Electronics Engineers (IEEE), the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) and the Spatial Web Foundation (SWF).

Building pervasive, open, and inclusive verses at a global scale will require cooperation and coordination between the constellation of international standards organizations mentioned before and other forms and associations, including the Metaverse Standards Forum (MSF) Khronos Group, World Wide Web Consortium (W3C), Open Geospatial Consortium (OGC), OpenAR Cloud, etc.

3GPP - 5G New Radio (NR) s designed to support emerging XR use cases requiring low latency, high reliability, lower power consumption, and high capacity. These demands may include quasi-periodic traffic in large chunks, irregular intervals, and variable size, as well as high data rates including uplink (UL) for AR services, simultaneous transmission of 3D video stream, and control data over the same end-to-end connection. 5G benefits XR, and the emerging use cases require further end-to-end optimisations and enhancements for 5G networks. Rel-15 and Rel-16 offer a foundation for XR, but they were not specifically designed or optimised for XR support. Enhancements in 3GPP Rel-17 and Rel-18 optimise XR support including XR awareness, power optimizations, and capacity enhancements. An overview of the 3GPP releases is given in Table I 1.

BSI – The standardisation activities related to immersive technologies are coordinated by IST/31 - Immersive Technologies committee, which is responsible for developing standards for immersive technologies (AR/MR/VR and XR) and for contributing to the work of ISO/IEC JTC 1/SC 24 developers of such standards as augmented reality continuum presentation and interchange, augmented reality continuum concepts and reference model and lastly, all matters of health, safety, security and usability of these technologies. IST/31/1 - Health, Safety, Security and Usability of Augmented Reality as Virtual Reality contributes to standardising information technology-based applications relating to AR and VR. IST/31/2 - Environmental Data and Image Processing contributes towards standardising information technology-based applications relating to environmental data representation and image processing.

IEEE – The standardisation activities related to immersive technologies, digital reality, AR, VR, human augmentation, and related areas are coordinated by IEEE Digital Reality in collaboration with IEEE-SA Augmented Reality Innovate Space as part of the IEEE Standards Association (IEEE-SA). The active working groups are AR-LEM - Augmented Reality Learning Experience Model and VR/AR - Virtual Reality and Augmented Reality Working Group. IEEE VR/AR Working Group is developing 12 standards for VR and AR. An overview of the standards developed by IEEE is given in Table I-1.

IEC - International Electrotechnical Commission (IEC). IEC Standardization Management Board has created a Systems Evaluation Group (SEG 15) to explore the needs of the metaverse. SEG 15 works to develop a common understanding and definition of the metaverse, investigate the need for standardization and provide recommendations for an initial roadmap. It engages with technical committees in IEC, as well as ISO and all other relevant organizations. Technical Committee 100 / Work Group 12 started in September 2023 two Projects. In the IEC standardisation flow, PWI stands for a preliminary stage and is related to "projects envisaged for the future but not yet ripe for immediate development", stressing the initial phase of Metaverse standardization in IEC. An overview of the two projects developed by IEC is given in Table I-1.

ISO – The standardisation activities related to immersive technologies, digital reality, AR, VR, human augmentation, and related areas are coordinated by IEEE Digital Reality in collaboration with IEEE-SA Augmented Reality Innovate Space as part of IEEE Standards Association (IEEE-SA). IEEE VR/AR Working Group is developing 12 standards for VR and AR. IEEE VR/AR Working Group is developing 12 standards for VR and AR. An overview of the standards developed by IEEE is given in Table I-1.

ITU-T – ITU Focus Group on metaverse coordinates the standardisation activities related to immersive technologies, digital reality, AR, VR, human augmentation, and related areas. An overview of the standards developed by SWF is given in Table I-1.

SWF – Spatial computing and the spatial web require technical standards supporting universal privacy, security, trust, and interoperability. Socio-technical standards for the spatial web are being developed jointly by the IEEE-SA and the SWF. The Spatial Web Protocol, Architecture and Governance specification defines the design for the Spatial Web™ system by specifying requirements for the interoperability and governance of cyber-physical systems at global scale, including autonomous devices, applications, spatial content, and operations.

SWF and IEEE-SA collaborate on the development of a socio-technical standard for the Spatial Web within the IEEE P2874 Spatial Web WG (Figure 8-2).

The Spatial web protocol, architecture, and governance include: Hyperspatial Modelling Language (HSML), Hyperspace Transaction Protocol (HSTP), and Universal Data Graph (UDG) implementation standards; policy guidance for spatial web federated governance, and domain architectures for various vertical applications.

A summary of the standards developed by SWF and the IEEE can be viewed in Table I-1.

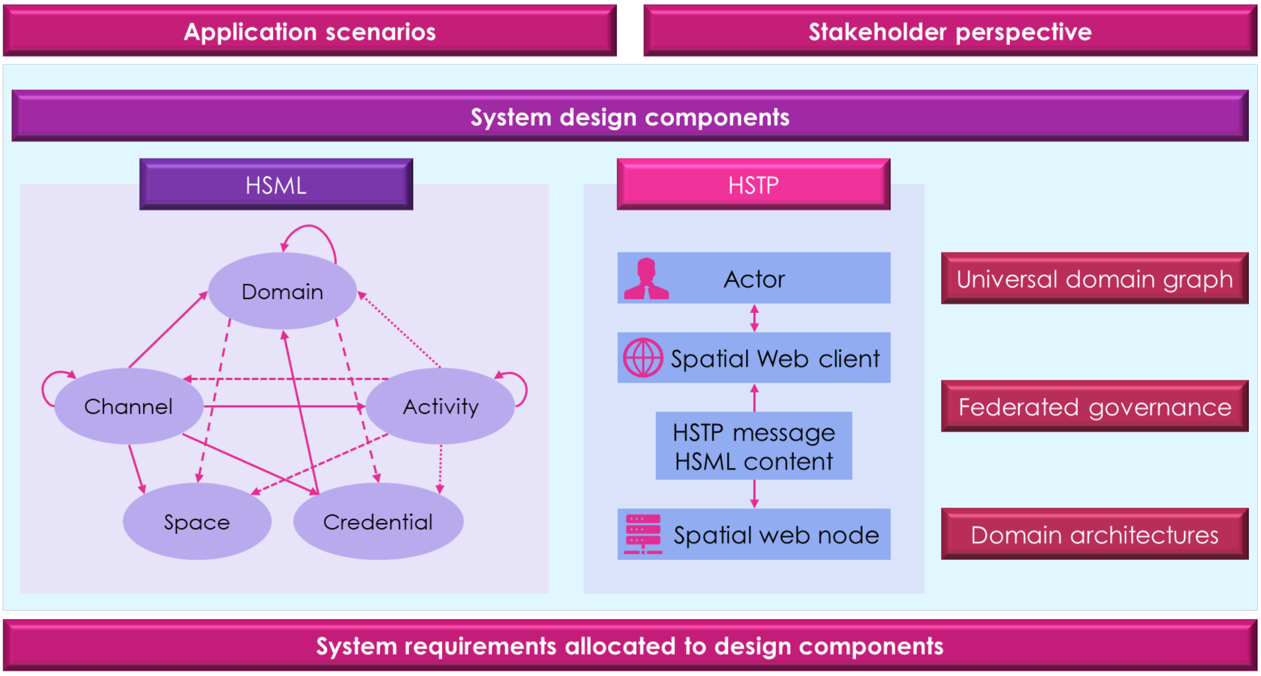

Figure 8-2 IEEE P2874 D2 system design components. Source: [55].

AOUSD - The Alliance for OpenUSD (AOUSD) is an open, non-profit organization dedicated to promoting the interoperability of 3D content through OpenUSD (Universal Scene Description). Standardising the 3D ecosystem enables developers and content creators to describe, compose, and simulate large-scale 3D projects and build an ever-widening range of 3D-enabled products and services. Part of the Joint Development Foundation, the Alliance brings together a diverse and inclusive community of participants to provide an open forum for collaborative development and discussion around OpenUSD.

MSF - The Metaverse Standards Forum (MSF) has as its mission to explore where the lack of interoperability is holding back metaverse deployment and how the work of Standards Developing Organizations (SDOs) defining and evolving needed standards may be coordinated and accelerated and focuses on pragmatic, action-based projects such as implementation prototyping, hackathons, plugfests, and open-source tooling to expedite the testing and adoption of metaverse standards, while also developing consistent terminology and deployment guidelines.

Khronos Group - is a non-profit consortium of companies involved in 3D graphics, AR, VR and machine learning, considering that the metaverse will bring together diverse technologies, requiring a constellation of interoperability standards created and maintained by many standards organisations. Khronos provides royalty-free open standards for 3D graphics, XR (VR and AR), parallel computing, ML, vision processing and metaverse. The portfolio of industry standards includes 3D Commerce, ANARI, glTF, Kamaros, KTX, NNEF, OpenCL, OpenGL, OpenGL ES, OpenVG, OpenVX, OpenXR, SPIR, SYCL, Vulkan, WebGL and different safety critical derivatives, including Vulkan SC, SYCL SC, OpenGL SC and the OpenVX safety critical profile.

W3C - World Wide Web Consortium (W3C) standards define an open web platform for application development. W3C and its partners are creating new technologies that extend the web and give it full strength, including CSS, SVG, WOFF, WebRTC, XML, and a growing variety of APIs.

OGC - Open Geospatial Consortium (OGC) – has formed the OGC Geo For Metaverse Domain Working Group, which serves as a forum for the collective geospatial expertise of the OGC community to gather to help build and grow the open metaverse. The geospatial community contributes to the metaverse via its expertise at scale in 3D, modelling and simulation, AI, DT, streaming, augmented and virtual realities, routing, mapping, etc.

OpenAR Cloud - drive the development of open and interoperable spatial computing technology, data and standards to connect the physical and digital worlds for the benefit of all. The organisation plan to design and build an open platform for the next era of computing, a reference Open Spatial Computing Platform (OSCP).

9. Future Technology Trends and Challenges

The convergence of the IoT, edge computing, AI, and industrial immersive technologies, such as VR, AR, MR, and verses (e.g., metaverse, omniverse, multiverse) and Web 4.0 technologies, is poised to create transformative changes across various sectors. Immersive online platforms enable humans and machines to collaborate and work remotely. Collaborative immersive working tools increase the harness of AR, VR, and MR to capture and express the more essential aspects of interaction that translate inadequately in the case of online interaction.

The integration and convergence of technologies promise to enhance operational efficiency, improve decision-making processes, and make more engaging and intuitive interfaces. Realising these benefits comes with its own set of challenges and implications.

Future Technology Trends

Seamless Integration of Digital and Physical Worlds: The convergence of these technologies will enable a more seamless integration of digital information with the physical environment, creating highly immersive and interactive experiences.

Autonomous Industrial Operations: With the integration of IoT, AI/ML, and edge computing, industries can move towards more autonomous operations. AI/ML algorithms can analyse data from IoT devices in real-time, making decisions and controlling machinery with minimal human intervention, thereby increasing efficiency, reducing errors and cost.

Sustainable system: The integration of immersive technology, IoT and Edge computing, correspondent to the technological growth of devices and communication system enables the decentralisation and remote operations in industry, with significant impact on emissions of greenhouse gasses. Immersive technologies can facilitate the shift towards using fewer environmentally damaging and non-recyclable materials by minimising physical waste in industrial processes. Developments in IoT, edge computing, AI, and industrial immersive technologies promote a significant transition to business models that substitute production and lifecycle management of physical items with digital services and assets. These technologies play a vital role in decreasing the demand for energy uses that heavily emit greenhouse gases, such as transportation, buildings, and heating and cooling, by enhancing mobility organisation, improving building energy efficiency, and optimising industrial processes. Sustainable immersive technologies require standards encompassing various sustainability facets, including energy efficiency, resource optimisation, circularity, and social responsibility. These measures extend across multiple disciplines and technologies to facilitate sustainability across different industries.

Personalised and Adaptive Interfaces: Immersive technologies, powered by AI/ML and IoT data, can create interfaces that adapt to individual users' preferences, learning styles, or performance, particularly in training and educational contexts. This personalisation can enhance learning outcomes and user engagement.

Predictive Maintenance and Analytics: Combining IoT sensors with edge computing and AI/ML can significantly improve predictive maintenance. By processing data on the edge, AI models can predict equipment failures before they occur, reducing downtime and maintenance costs.

Enhanced Trust: As more sensitive data is processed locally on edge devices rather than transmitted to the cloud, there's potential for improved data privacy. However, this also necessitates advanced security protocols to protect against local data breaches and ensure the integrity of AI operations.

AI-powered 3D and Virtual Spaces: Fusion of the real and virtual world through immersive triplets, 3D spaces powered by generative AI, AI-driven assistants, and AI-powered avatars.

Democratising 3D Immersive Technologies and Applications: Expanding immersive digital experiences and collaborations with the development of interoperable platforms seamlessly integrate the digital and physical worlds into everyday lives, promising inclusivity, and universally accessible immersive experiences. Immersive triplets, DTs combined with Building Information Modelling (BIM), enhance efficiency and precision in various industrial sectors.

Multi-Sensory and Multi-Actuation 3D Immersive Technologies: Progress is being made in the IoTS to create devices that enhance the sensation of immersion in digital worlds and provide multi-sensory and multi-actuation experiences.

Challenges

Advanced HW and edge IoT devices: Devices designed to create with reduced power envelope immersive experiences, including headsets, AI-based sensors/actuators, cameras, intelligent connectivity, controllers, and haptic devices that provide physical feedback.

New SW and CAD platforms: Designing open and compatible platforms to create digital environments and experiences that enable seamless interaction between users and HW, ensuring a cohesive user interface.

Programming languages, libraries, and SW development kits (SDKs): Development for programming environments used to build immersive environments ranging from realistic simulations to advanced tools and AI frameworks for designing and creating engaging experiences.

User interface (UI): Improving HMI and UI to enhance interaction with the digital environment for a more immersive experience. User's ability to interact with the digital environment depends on the simplicity and intuitiveness of interfaces feedback which must be optimised to the user's task.

Intelligent connectivity: Accelerate the advancement of multi-protocol, multi-frequency smart wireless, cellular technologies, multi-domain (satellite and terrestrial) and real-time intelligent mesh hyperconnectivity.

Blockchain and NFTs: Blockchain may be a critical immersive technology element to ensure greater security and privacy. Blockchain digital identity technologies can enable industries to manage better with whom they interact or optimise the interactions between different machines and digital components. NFTs based on blockchain technology may prove the existence, authenticity, and ownership of content and assets in the industrial edge IoT immersive technologies that enable value creation throughout the digital asset life cycle and allow for new business models (e.g., immersive triplets, DT trading).

Edge IoT immersive platforms: Edge IoT digital platforms and marketplaces will be important in providing open, flexible IoT industrial immersive solutions. This requires open, interoperable solutions that allow seamless, real-time, concurrent collaboration, open APIs, compatible data formats, and protocols. The goal is to integrate the edge IoT industrial immersive technologies using a common language that facilitates users' connecting their immersive triplets, avatars, and DTs in the digital, virtual, and cyber worlds. Industries can use interoperable, open systems and standard platforms to connect their immersive triplets, avatars, and DTs with the counterparts of their partners and suppliers, creating larger ecosystems that produce more profound insights and plug-and-play solutions. Appropriate regulation must ensure and encourage collaboration and interoperability by handling privacy and security concerns and protecting intellectual property in digital assets in edge IoT industrial immersive spaces.

High-quality, robust, reliable, and affordable immersive technologies: Development of integrated and miniaturised semiconductors, IoT devices, edge processing, and AI/ML technologies for implementing intelligent IIoT immersive technologies.

Integration of immersive technology: Development of system-of-systems concepts, approaches, and frameworks for integrating edge IoT industrial immersive technologies and the spatial computing continuum with existing systems in various industries. Development of web-based 3D immersive solutions to enhance digital experiences on web-based platforms that eliminate the need for app downloads, providing immediate and universal access on various devices.

Interoperability and Standardisation: With a vast array of edge IoT immersive devices, platforms, and technologies, ensuring interoperability among different systems is a significant challenge. Standardisation efforts are crucial to enable seamless communication and integration across devices and platforms. Especially the interlock and synergy between the several SDOs involved in the immersive technology domain calls for a joint world-wide effort in delivering aligned and non-controversial technical specifications mandated by the different Work Groups.

Data Privacy and Security: While edge computing can enhance data privacy, the increased distribution of data processing points expands the attack surface for potential breaches. Ensuring robust security measures that can operate effectively in decentralised environments is essential.

Scalability: As the number of connected edge IoT immersive devices and the volume of data they generate grow, developing scalable solutions that can handle this increase efficiently without compromising performance is a significant challenge.

Complexity in Deployment and Management: The convergence of these technologies increases the complexity of deploying and managing fully immersive systems. New skill sets and knowledge are needed to implement and maintain these integrated systems effectively.

Ethical and Societal Implications: The widespread adoption of immersive technologies raises ethical questions concerning privacy, surveillance, and the potential displacement of jobs due to automation and AI/ML introduction. This is also a concern as the more sophisticated the HMDs get the more biodata they will collect, even reaching the point of private medical data. Addressing these concerns requires careful consideration and the development of ethical guidelines and policies. European regulations play a pivotal role in this regard and must follow close the advancement of the technology in the field of immersive technologies.

Interdisciplinary Integration: The development of immersive technologies requires engagement in interdisciplinary activities that demand comparing disciplines, understanding disciplines, and thinking between disciplines to stimulate the co-creation of solution-oriented transferable knowledge. The immersive technology design focuses on integrated research through multidisciplinary group work of experts and non-experts interconnected into a transdisciplinary framework, as the immersive concept is a multidimensional complex of disciplinary interrelations that require learning to think at the interfaces between disciplines.

Collaboration Across the Technology Spectrum: IoT, connectivity, computing, and AI are converging, and stakeholders in different segments of the value chain need to work together, including chip manufacturers, supply chain providers, IoT and electronic communications network equipment providers, AI solutions developers, edge, cloud service providers, and immersive applications providers.

10. Conclusions

The convergence of IoT, edge computing, AI, and industrial immersive technologies holds great promise for transforming industries and enhancing human capabilities. However, realising this potential requires overcoming significant challenges, including interoperability, privacy, energy consumption, security, legal and ethical considerations.

Success in this endeavour depends on collaborative efforts among research communities, technologists, industry leaders, standardisation bodies, policymakers, and the broader society to develop innovative solutions and frameworks that can effectively address these challenges while maximising the benefits of these converging immersive technologies.

Concentrated and aligned efforts in technological development, orchestration, standardisation, interoperability, and research at the European level are needed to overcome the challenges and use the opportunities that arise from the convergence of IoT, edge computing, AI, and industrial immersive technologies.

The convergence and fusion of technologies such as IoT, AI, intelligent connectivity with DTs, immersive triplets, and cloud data exchange facilitate the development and deployment of VR, AR, MR, XR, and various verses (metaverse, omniverse, multiverse), inherently require a highly interdisciplinary approach. The multidisciplinary nature of these technologies involves multiple fields, such as computer science, electrical engineering, data science, user experience design, cognitive science, and more.

The systems-of-systems integration of these technologies signifies a technological shift, as well as a cultural and economic one, potentially altering how we perceive and interact with the digital and physical worlds. This convergence promises a more integrated, immersive, and interactive future.

Technological Synergy: The convergence of IoT, AI, intelligent connectivity, and immersive technologies such as VR, AR, MR, and XR at the edge, combined with DTs and immersive triplets, creates a powerful platform for innovation in industrial applications. This synergy facilitates advanced simulations, real-time operations, and enhanced user interactions, driving forward the concept of the industrial verses.

European Industrial Leadership: European leadership in sectors such as automotive, aerospace, manufacturing, energy, and health provides a solid foundation for the adoption and integration of these converging technologies. This existing industrial base can pioneer the development of systems-of-systems integration crucial for realizing industrial verses.

Maturity of the Industrial Metaverse: The industrial metaverse is currently more advanced than its consumer counterparts, primarily due to the higher readiness and immediate applicability of DTs and AI in industrial settings. This maturity offers a strategic advantage in deploying these technologies more rapidly and effectively.

Generative and Contextual Technologies: The role of next-generation IoT and generative AI in creating context-aware, dynamically adaptive industrial environments is significant. These technologies allow for more sophisticated and tailored immersive experiences, enhancing operational efficiency and decision-making processes.

Invest in Research and Development: Encourage and fund research and innovation projects integrating AI, IoT, DTs, immersive triplets, intelligent connectivity, and immersive technologies. This investment should solve specific industrial challenges and push the boundaries of what's currently possible in immersive assets accuracy and real-time data analytics.

Allocate significant resources towards research and development to continuously advance the capabilities of edge IoT and immersive technologies. This should include the exploration of new materials, sensors, algorithms, and user interfaces.

Promote Standards and Interoperability: Develop and promote industry-wide standards to ensure interoperability among different technologies and platforms. This will facilitate systems-of-systems integration and allow seamless interactions between various components of the industrial metaverse. Align the activities with the regulations and requirements in the European Data, AI, Cybersecurity and Chips Acts.

Implement Pilot Projects and Scalability Tests: Encourage the development of a European framework to address the verification, validation and testing of AI-based immersive technologies. Launch pilot projects within key industrial sectors to test the feasibility and effectiveness of these technologies. Evaluate performance, gather user feedback, and scale successful practices across other sectors and markets.

Stimulate Regulatory and Policy Support: Work closely with regulatory bodies to create guidelines that support the deployment of the immersive edge IoT, AI, DTs, IMTs, intelligent connectivity, IoTS, SDA, spatial computing verses and Web 4.0, while ensuring safety and ethical considerations. Promote policies that encourage the adoption of next-generation technologies in industrial settings.

Extend Public-Private Partnerships: Establish partnerships between public authorities, research, academic institutions, and industry leaders. These collaborations can accelerate technology transfer, scale innovations, and align strategic interests across sectors.

Enhance Skills and Education: Implement training programs and update educational curricula to include skills relevant to emerging technologies like AI, IoT, and immersive technologies. Preparing a workforce adept at navigating and optimising these technologies is crucial.

Strengthen Interdisciplinary Collaboration: Foster collaboration and coordination between European partnerships and initiatives to enhance the interdisciplinary exchange of knowledge and to spur innovation in edge IoT and immersive technologies. Establish joint task forces or innovation clusters where these collaborations can thrive.

Enhance IoT and Edge Computing, HW, SW, AI Technology Stack and Data Integration: Invest in developing robust HW, AI, data, and data sets that can withstand industrial environments and efficiently support immersive technologies. Parallelly, promote SDA to allow flexible, scalable, and cost-effective solutions.

Improve Workflow Integration: Design integration protocols and tools that enable seamless embedding of IoT and immersive technologies into existing industrial workflows to support the integration of systems of-systems for immersive applications. Provide modular solutions that can be customised for different industrial needs to minimise disruption and enhance adoption.

Create Interdisciplinary projects: Establish dedicated research and innovation projects focused on the convergence of these technologies. These projects can serve as references for interdisciplinary innovation, bringing together experts from various fields to focus on shared goals and challenges in industrial immersive technologies and applications across industrial sectors and platforms. By creating these projects, collaborative efforts can be streamlined and more effectively directed towards innovative solutions that span multiple industries and disciplines. This will ultimately enhance the development and deployment of integrated technologies in the realm of IoT, AI, and immersive environments.

Secure Data and Protect Privacy by Providing a Trustworthy Framework for Immersive Technologies Development: Implement advanced dependable measures tailored to the immersive edge computing environment to protect sensitive industrial data and provide trustworthy design and operation mechanisms for industrial immersive applications. Adopt trust-preserving technologies, to ensure that data exploitation does not compromise system robustness, reliability, scalability, interoperability, security, safety, and reliability.

Establish Collaborative Platforms: Create platforms where professionals from different disciplines can meet, share ideas, and collaborate on projects. This could be through regular interdisciplinary workshops, seminars, and joint research initiatives.

Foster Academic and Industry Partnerships: Encourage partnerships between academia and industry to combine theoretical knowledge with practical applications. These partnerships can provide mutual benefits—academics gain insight into real-world challenges, and industry players access cutting-edge research.

Secure Digital and Connectivity Infrastructure: As reliance on interconnected technologies grows, robust cybersecurity measures are essential. Develop secure connectivity infrastructure and protocols to protect sensitive industrial data and maintain operational integrity against threats. Upgrade network infrastructure to support high-speed, low-latency communications essential for immersive and edge computing applications including the expansion of 5G/6G networks and advanced Wi-Fi technologies.

Support Startups and Innovation: Encourage startups by providing financial, technical, and mentorship support. Startups often drive innovation in cutting-edge immersive technologies, and their agile nature enables rapid adaptation and development of novel solutions.

During the next decade European industries can effectively leverage the convergence of edge IoT, AI, and immersive technologies to transform industrial operations, enhancing efficiency, safety, and decision-making capabilities while fostering a competitive edge in the global market.

By addressing and adopting these recommendations, European industrial sectors can enhance their global competitiveness and lead in developing and applying sustainable, cutting-edge technologies within the industrial immersive technologies and applications, fostering growth and innovation in a rapidly evolving twin digital and green physical and virtual landscape.

This position paper on edge IoT industrial immersive technologies will be followed by a new position paper on edge IoT industrial immersive applications across industrial sectors, which is planned to be released in the autumn of 2024.

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Acknowledgements

About AIOTI

AIOTI is the multi-stakeholder platform for stimulating IoT and Edge Computing Innovation in Europe, bringing together small and large companies, academia, policy makers and end-users and representatives of society in an end-to-end approach. We work with partners in a global context. We strive to leverage, share, and promote best practices in the IoT and Edge Computing ecosystems, be a one-stop point of information on all relevant aspects of IoT Innovation to its members while proactively addressing key issues and roadblocks for economic growth, acceptance, and adoption of IoT and Edge Computing Innovation in society. AIOTI's contribution goes beyond technology and addresses horizontal elements across application domains, such as matchmaking and stimulating cooperation in IoT and Edge Computing ecosystems, creating joint research roadmaps, driving convergence of standards and interoperability, and defining policies.

Annex I. Immersive Technologies Standardisation – SDOs Activities

Table I-1 Standardisation activities related to immersive technologies across various SDOs.

Standardisation Organisations	
Standards	**Description and comments**
3GPP – 3rd Generation Partnership Project	
Rel-15	3GPP Work Groups (WGs) started back in 2017 to focus on immersive technologies-related work with 3GPP Release 15 (Rel-15). Rel-15 added new capabilities to support XR services, thanks to the introduction in RAN WGs of some new features that aimed at helping reducing delays, thanks to the decrease of communication latency, for instance the features down link (DL) pre-emption and Grant-free transmission, or enhance reliability of the connections, for instance thanks to the introduction of a Priority indicator.
Rel-16	Rel-16 is the first 3GPP release that explicitly addresses XR, in the Technical Report (TR) 26.928 'Extended Reality (XR) in 5G', which had the charter of defining a roadmap for future work in 3GPP WGs, mentioning several areas suited for standardization. It also listed a set of potential XR use cases, and provided a survey of 3D, XR visual and audio formats.
Rel-17	In 2020 Rel-17 produced the first technical specification (TS) on XR, i.e., TS 22.261 "XR and Cloud gaming use cases" and several other TRs, among which the most notable was the TR 38.838 "Study on XR enhancements for NR", which introduced some new features to improve the capacity of the cellular system to cover more users using XR services and to considerably reduce the energy consumption of such services. Additional enhancements can be listed as follows: enhancements in data speeds, reduced latency, and ultra-reliability. These encompass Multiple In Multiple Out (MIMO) for 5G New Radio (NR), Improved Uplink Coverage, Enhanced Sidelink Communications, Positioning Enhancement, UE Power Saving, Ultra-Reliable Low Latency Communications (URLLC)/ IIoT Enhancements, Integrated Access and Backhaul (IAB), and Non-Terrestrial Networks (NTN). Support to Metaverse and Reduced Capability (RedCap) devices were also introduced for applications like those running in wearables (e.g., smartwatches, wearable medical devices, augmented reality (AR)/VR goggles, industrial wireless sensors, and video surveillance). ML coverage was expanded to provide descriptions of principles for RAN intelligence enabled by ML.
Rel-18	Rel-18 introduced support for new services like tactile internet and for applications aiming at delivering immersive experiences to users, see TR 22.847, TS 22.261, TR 23.700, and a long list of new TRs and TS mainly driven by the SA4 WG). Other features introduced of relevance to immersive technologies are protocol optimizations of the XR support including XR awareness, increased power reduction in operating XR services, and capacity enhancements, the latter especially thanks to the introduce new feature joint communication and sensing (JCAS), which integrates communication and sensing functionalities within the same system or network. Rel-18 also extends the use of ML/AI to most of the specifications.
Rel-19	The recently started Rel-19 is the first 3GPP release to address directly the Metaverse, via the new TR 22.856 "Study on localized mobile Metaverse services", TS 22.156 "Mobile Metaverse services", and TS 22.261 "Supporting EU mobility for XR services". New Rel-19 Work Items are also starting in RAN and SA WGs, e.g., the "XR Evolution" and the "Network energy savings", whereas work in CT WGs has just very recently started (Q2 2024). Additional supported features are planned to be "Localised mobile metaverse services" and "XR for NR Phase 3". Further extensions to AI/Ml features are planned as well, e.g., the WI "AI/ML for NR air interface" under acronym "NR_AIML_air".
(Rel-20)	No Rel-20 activity has yet started in any 3GPP WG as of Q2 2024. Rel-20 Is the release that will first work on 6G specifications, a set of technical reports (TRs) are planned to be provided, mainly based on defining 6G use cases and requirements of the to-be defined 6G architecture. AI/ML are expected to be natively integrated in all 6G specifications, marking 6G as the first generation of data-driven mobile networks.
(Rel-21)	Rel-21 will be the first release to mandate in Technical Specifications (TS) the first set of 6G features and related protocol messages and description of the 6G

	architectural layers and building blocks of the 6G CN and RAN architecture. The first TS are expected not before the 2028 timeframe.
IEEE SA- Institute of Electrical and Electronics Engineers Standard Association	
IEEE 802.11ax™	Wi-Fi 6 is designed to get better efficiency using increased throughput in 2.4, 5 and 6 GHz bands. Modifications to both the IEEE 802.11 physical layer (PHY) and medium access control (MAC) sublayer for high-efficiency operation in frequency bands between 1 GHz and 7.125 GHz are defined in this amendment to IEEE Std 802.11-2020.
IEEE P802.11be™	Wi-Fi 7 with 4x faster data rates (~40 Gbit/s) and twice the bandwidth (320 MHz channels vs. 160 MHz channels for Wi-Fi 6). It also supports more efficient and reliable use of the available and contiguous spectrum through multi-band/multi-channel aggregation and other means. The standard features numerous enhancements to MIMO protocols and many other advancements and refinements of existing Wi-Fi capabilities. The capabilities match the requirements for AR/VR and verses applications. IEEE 802.11-based Wi-Fi networks carry an extensive and growing amount of data, making it possible to leverage new AI/ML algorithms, such as federated learning, to improve Wi-Fi performance and user experiences. The IEEE 802.11 Extremely High Throughput Study Group has been established to explore new IEEE 802.11 features for bands between 1 and 7.125 GHz that would increase peak throughput to support these demanding applications.
IEEE 2888.1-2023	IEEE Standard for Specification of Sensor Interface for Cyber and Physical Worlds. The vocabulary, data formats, and application programming interfaces (APIs) for acquiring information from sensors are defined in this standard, enabling communication between the cyber world and the physical world.
IEEE 2888.2-2023	IEEE Standard for Actuator Interface for Cyber and Physical Worlds. The vocabulary, data formats, and application programming interfaces (APIs) for controlling the actuators, which helps enable the definition of interfaces between the cyber world and the physical world, are defined in this standard.
IEEE P2888.3	Standard on Orchestration of Digital Synchronization between Cyber and Physical Worlds. This standard defines the vocabulary, requirements, metrics, data formats and application program interfaces (APIs) for setting up parameters for and communicating with digital objects to provide sequences of synchronization and interaction with physical objects.
IEEE 2888.4-2023	IEEE Standard for Architecture for Virtual Reality Disaster Response Training System with Six Degrees of Freedom (6 DoF). Defined in this standard is a reference architecture required for building a virtual reality (VR) training system for large space disaster response.
IEEE P2888.5	IEEE Draft Standard for Virtual Training System Evaluation Methods. This standard defines the evaluation methods and frameworks for virtual training systems. The evaluation framework consists of a plan, design, data, test, and analysis that can evaluate the virtual training systems' effectiveness, usability, and acceptability.
IEEE P2888.6	Standard for Holographic Visualization for Interfacing Cyber and Physical Worlds. This standard defines representations of holographic content to provide interfaces between Cyber and Physical Worlds for objects, which may exist either in Cyber or Physical Worlds. This includes following formats and scheme: Holographic printing file format, Holographic contents, etc.
IEEE 1589-2020	IEEE Standard for Augmented Reality Learning Experience Model. Defines two data models and their binding to XML and JSON for representing learning activities (also known as employee tasks and procedures) and the learning environment in which these tasks are performed (also known as the workplace). The interoperability specification and standard are presented in support of an open market where interchangeable component products provide alternatives to monolithic AR-assisted learning systems. Moreover, it facilitates the creation of experience repositories and online marketplaces for AR-enabled learning content.
IEEE P7016.1	Standard for Ethically Aligned Educational Metadata in Extended Reality (XR) & Metaverse. defines a high-level overview of a conceptual data schema for a metadata instance based on ethics concepts for a learning object utilized within XR systems and Metaverse applications. This standard does not aim to define whether procedures and operations as presented through the Metaverse are ethical or not. This standard does not involve evaluation of the ethical value of learning content objects. Use case examples of the conceptual data schema are defined. This standard also describes a high-level ethical design methodology of learning objects for XR and the Metaverse applications, using the IEEE Std 7000 applied ethical approach.
IEEE IC15-004-01	3D Body Processing

IEEE IC16-004-02	Augmented Reality in the Oil/Gas/Electric Industry
IEEE IC16-005-02	Consumer Healthcare Alliance
IEEE P2048	Standard for Metaverse: Terminology, Definitions, and Taxonomy. This is the most relevant of the projects (P) that started on the Metaverse in IEEE. IEEE P2048 has the charter to create a common understanding in the international ecosystem on categories and levels of what will be called Metaverse. The work started in 2023 and is supposed to be completed by 2026.
IEEE P2048.1	Standard for Virtual Reality and Augmented Reality: Device Taxonomy and Definitions
IEEE P2048.2	Standard for Virtual Reality and Augmented Reality: Immersive Video Taxonomy and Quality Metrics
IEEE P2048.3	Standard for Virtual Reality and Augmented Reality: Immersive Video File and Stream Formats
IEEE P2048.4	Standard for Virtual Reality and Augmented Reality: Person Identity
IEEE P2048.5	Standard for Virtual Reality and Augmented Reality: Environment Safety
IEEE P2048.6	Standard for Virtual Reality and Augmented Reality: Immersive User Interface
IEEE P2048.7	Standard for Virtual Reality and Augmented Reality: Map for Virtual Objects in the Real World
IEEE P2048.8	Standard for Virtual Reality and Augmented Reality: Interoperability between Virtual Objects and the Real World
IEEE P2048.9	Standard for Virtual Reality and Augmented Reality: Immersive Audio Taxonomy and Quality Metrics
IEEE P2048.10	Standard for Virtual Reality and Augmented Reality: Immersive Audio File and Stream Formats
IEEE P2048.11	Standard for Virtual Reality and Augmented Reality: In-Vehicle Augmented Reality
IEEE P2048.12	Standard for Virtual Reality and Augmented Reality: Content Ratings and Descriptors
IEEE P2048.111	Standard for Technical Specification for Three-dimensional (3D) Reconstruction and Visual Localization for Large-Scale Scenes. This standard specifies a structure of a large-scale scene (indoor or outdoor scenes with an area of more than 300 m^2), oriented 3D reconstruction and visual localization system, the functional requirements, and basic performance requirements and test methods.
IEEE P2048.121	Standard for General Technical Requirements for Service-oriented Digital Human Based on Artificial Intelligence. This standard specifies a reference framework and requirements for the functionality and performance of service-oriented digital humans based on artificial intelligence (AI). This standard provides guidance for design, development, testing, application, and management of service-oriented digital human based on AI.
IEEE P2048.201	Standard for Security Specification of Blockchain-based Metaverse Accounts. This standard specifies the security requirements for consumer's personal accounts and public accounts of blockchain-based Metaverse technology, including general account requirements, basic security requirements, and service security requirements.
IEEE P2874	Standard for Spatial Web Protocol, Architecture and Governance. This standard describes a Hyperspace Transaction Protocol (HSTP) that enables interoperable, semantically compatible connections between connected hardware (e.g. autonomous drones, sensors, smart devices, robots) and software (e.g. services, platforms, applications, artificial intelligence systems). The Spatial Web Protocol, Architecture and Governance specification defines requirements for the interoperability and governance of cyber-physical systems at a global scale, including autonomous devices, applications, spatial content, and operations. The full specification is developed by the Spatial Web Foundation and the IEEE P2874 Spatial Web, Architecture and Governance Working Group. The system design includes: a shared and linkable knowledge domain architecture ("Architecture"); a common language with which to describe domain elements and their interrelationships – HSML; a method for querying and updating the states of those elements ("Protocol") – HSTP; the ability to allow access and control of that method ("Governance"), and a Universal Domain Graph. Collectively these elements are the Spatial Web Standards ("Standards").
IEEE 3079-2020	IEEE Standard for Head-Mounted Display (HMD)-Based Virtual Reality (VR) Sickness Reduction Technology. Defines the technical requirements that can reduce or control the VR sickness caused by the HMD-based VR content service. The VR content service mentioned in this document is considered HMD-based VR content service by default unless otherwise mentioned. The requirements cover the

	followings: Content design for VR sickness reduction - The framework for VR sickness assessment; The measurement and the network requirements related to motion-to-photon latency for VR sickness reduction.
IEEE P3141	Standard for 3D Body Processing. This standard addresses the anthropometric and topo-physiological attributes that contribute to the quality of experience of 3D body processing, as well as identifying and analysing metrics and other useful information, as well as data relating to these attributes.
IEC - International Electrotechnical Commission	
IEC	IEC / Technical Committee 100 / Work Group 12 started in September 2023 the following two Projects. It is worth noting that in the IEC standardization flow, PWI stands for a preliminary stage and is related to "projects envisaged for the future but not yet ripe for immediate development", stressing the initial phase of Metaverse standardization in IEC.
IEC/PWI TR 100-58	Definitions and Classifications of Metaverse
IEC/PWI TR 100-59	Gap Analysis for Metaverse Systems and Equipment
ISO - International Organization for Standards	
ISO/IEC 23005-1:2020	Specifies the architecture of MPEG-V (media context and control) and its three types of associated use cases: information adaptation from virtual world to real world; information adaptation from real world to virtual world; information exchange between virtual worlds.MPEG-V (Media context and control) provides an architecture and specifies associated information representations to enable the interoperability between virtual worlds, e.g., digital content providers of a virtual world, (serious) gaming, simulation, and with the real world, e.g., sensors, actuators, vision and rendering, robotics. MPEG-V is applicable in various business models/domains for which audiovisual contents can be associated with sensorial effects that need to be rendered on appropriate actuators and/or benefit from well-defined interaction with an associated virtual world.
ISO/IEC 23005-2:2018	Information technology - Media context and control, Part 2: Control information. Specifies syntax and semantics of the tools required to provide interoperability in controlling devices (actuators and sensors) in real as well as virtual worlds: Control Information Description Language (CIDL) as an XML schema-based language which enables one to describe a basic structure of control information; Device Capability Description Vocabulary (DCDV), an XML representation for describing capabilities of actuators such as lamps, fans, vibrators, motion chairs, scent generators, etc.; Sensor Capability Description Vocabulary (SCDV), interfaces for describing capabilities of sensors such as a light sensor, a temperature sensor, a velocity sensor, a global position sensor, an intelligent camera sensor, etc.; Sensory Effect Preference Vocabulary (SEPV), interfaces for describing preferences of individual user on specific sensorial effects such as light, wind, scent, vibration, etc.; Sensor Adaptation Preference Vocabulary (SAPV), interfaces for describing preferences on a sensor of an individual user on each type of sensed information.
ISO/IEC 23005-3:2019	Information technology - Media context and control. Part 3: Sensory information. Specifies syntax and semantics of the tools describing sensory information to enrich audio-visual contents: Sensory Effect Description Language (SEDL) as an XML schema-based language which enables one to describe a basic structure of sensory information; Sensory Effect Vocabulary (SEV), an XML representation for describing sensorial effects such as light, wind, fog, vibration, etc. that trigger human senses.
ISO/IEC 23005-4:2018	Information technology - Media context and control. Part 4: Virtual world object characteristics. Specifies syntax and semantics of the tools used to characterize a virtual world object related metadata: Virtual World Object Characteristics (VWOC) as an XML Schema-based language which enables one to describe a basic structure of avatars and virtual world objects in virtual environments.
ISO/IEC 23005-5:2019	Information technology - Media context and control, Part 5: Data formats for interaction devices. Specifies syntax and semantics of the data formats for interaction devices by providing a standardized format for interfacing actuators and sensors by defining XML schema-based language named Interaction Information Description Language (IIDL). IIDL provides a basic structure with common information for communication with various actuators and sensors in consistency. Device Command Vocabulary (DCV) is defined to provide a standardized format for commanding individual actuator, and Sensed Information Vocabulary (SIV) is defined to provide a standardized format for holding information from individual sensors either to get environmental information from real world or to influence virtual world objects using the acquired information based on IIDL.

ISO/IEC 23005-6:2019	Information technology - Media context and control, Part 6: Common types and tools. Provides definitions of data types and tools, which are used in other parts of the ISO/IEC 23005 series but are not specific to a single part.
ISO/IEC 23005-7:2019	Information technology - Media context and control. Part 7: Conformance and reference SW. Specifies the conformance and reference SW implementing the normative clauses of all parts of the ISO/IEC 23005 series. The information provided is applicable for determining the reference SW modules available for the parts of the ISO/IEC 23005 series, understanding the functionality of the available reference SW modules, and utilizing the available reference SW modules.
ISO/IEC TR 23844:2023	Specifies potential directions for using immersive technologies in learning, education, and training (LET) and provides suggestions on what can be standardized for this purpose. For the purposes of this document, immersive technologies include augmented reality (AR), virtual reality (VR), mixed reality or merged reality (MR). The document does not apply to technologies such as metaverse, digital twin and extended reality (XR).
ITU - International Telecommunication Union - Technical Reports and Specifications	
FGMV	The ITU-T Focus Group on Metaverse (FG-MV) started in December 2022 and is composed of a broad set of planned activities, described in the following items.
FGMV-01	Exploring the metaverse: opportunities and challenges.
FGMV-02	Metaverse: an analysis of definitions.
FGMV-20	Definition of metaverse.
FGMV-21	Principles for building concepts and definitions related to metaverse.
FGMV-24	A framework for confidence in the metaverse.
FGMV-25	Near-term and long-term Implications for people in the metaverse.
FGMV-09	Power metaverse: Use cases relevant to grid side and user side.
FGMV-22	Capabilities and requirements of generative artificial intelligence in metaverse applications and services.
FGMV-27	Guidelines for metaverse application in power system.
FGMV-28	Requirements for the metaverse based on digital twins enabling integration of virtual and physical worlds.
FGMV-29	Reference model for the metaverse based on a digital twin enabling integration of virtual and physical worlds.
FGMV-19	Service scenarios and high-level requirements for metaverse cross-platform interoperability.
FGMV-06	Guidelines for consideration of ethical issues in standards that build confidence and security in the metaverse.
FGMV-10	Cyber risks, threats, and harms in the metaverse.
FGMV-11	Embedding safety standards and the user control of Personally Identifiable Information (PII) in the development of the metaverse.
FGMV-12	Children's age verification in the metaverse.
FGMV-13	Responsible Use of AI for Child Protection in the metaverse.
FGMV-23	Considering online and offline implications in efforts to build confidence and security in the metaverse.
FGMV-07	Policy and regulation opportunities and challenges in the metaverse.
FGMV-14	Regulatory and economic aspects in the metaverse: Data protection-related.
FGMV-03	Guidelines to assess inclusion and accessibility in metaverse standard development
FGMV-04	Requirements of accessible products and services in the metaverse: Part I – System design perspective.
FGMV-05	Requirements of accessible products and services in the metaverse: Part II – User perspective.
FGMV-08	Design criteria and technical requirements for sustainable metaverse ecosystems.
FGMV-15	Accessibility requirements for metaverse services supporting IoT.
FGMV-16	Accessibility in a sustainable metaverse.
FGMV-17	Guidelines and requirements on interpreting in the metaverse.
FGMV-18	Guidance on how to build a metaverse for all – Part I: Legal Framework.
FGMV-26	Requirements for communication between human-avatar languages in the metaverse.