NEXT G ALLIANCE
An ATIS Initiative

6G

Next G Alliance Report:
Multi-Sensory Extended Reality (XR) in 6G

ABSTRACT

Four foundational activity areas — Everyday Living, Experience, Critical Roles, and Societal Goals — have been identified as applicable to the introduction of new digital immersive technologies for the 6G era. This paper identifies the promise of Multisensory Extended Reality (XR), surveys the current state of the technology and the XR's evolution from 5G, and identifies requirements to advance XR applications to include potential research areas.

FOREWORD

As a leading technology and solutions development organization, the Alliance for Telecommunications Industry Solutions (ATIS) brings together the top global ICT companies to advance the industry's business priorities. ATIS' 150 member companies are currently working to address network reliability, 5G, robocall mitigation, smart cities, artificial intelligence (AI)-enabled networks, distributed ledger/blockchain technology, cybersecurity, IoT, emergency services, quality of service, billing support, operations and much more. These priorities follow a fast-track development lifecycle from design and innovation through standards, specifications, requirements, business use cases, software toolkits, open-source solutions, and interoperability testing.

ATIS is accredited by the American National Standards Institute (ANSI). ATIS is the North American Organizational Partner for the 3rd Generation Partnership Project (3GPP), a founding Partner of the oneM2M global initiative, a member of the International Telecommunication Union (ITU), as well as a member of the Inter-American Telecommunication Commission (CITEL).

For more information, visit www.atis.org. Follow ATIS on Twitter and on LinkedIn.

The ATIS 'Next G Alliance' is an initiative to advance North American wireless technology leadership over the next decade through private-sector-led efforts. With a strong emphasis on technology commercialization, the work will encompass the full lifecycle of research and development, manufacturing, standardization, and market readiness.

TABLE OF CONTENTS

1 PURPOSE OF WHITE PAPER

By 2030, Multisensory Extended Reality (XR) is expected to transform the telecommunication industry by introducing an estimated 1 billion XR glasses and sensory devices along with associated computational services that will be integrated with network infrastructure. Innovations in lightweight XR glasses, brain-computer interfaces [1], and lightweight haptics wearables will pave the way for massive global deployment of multisensory XR. The applications and solutions for XR will have the potential for profound socioeconomic impact. Multisensory XR can unleash an unprecedented variety of applications and services in entertainment, gaming, education, public safety, health care, transportation, communication, manufacturing, and retail. This paper highlights XR's requirements, potential, challenges, and socioeconomic impact.

2 BACKGROUND

XR is an umbrella term that covers immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). XR often integrates sensors and actuators using tactile feedback, and stimulation of senses such as smell and taste.

In VR, users are totally immersed in a simulated digital environment or a digital replica of reality. MR includes all variants where virtual and real environments are mixed. AR is one such variant, where 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. MR can also include variants where real objects are included in the virtual world.

XR is viewed as the next step toward seamlessly merging and integrating physical and digital worlds. The ecosystem for futuristic applications will establish crucial requirements for the next generation of cellular technology.

XR will have immense impact on global communities. Nascent XR applications are beginning to advance sustainability goals. As the technology matures and usage becomes widespread, it is anticipated that the quality of life for millions will be improved.

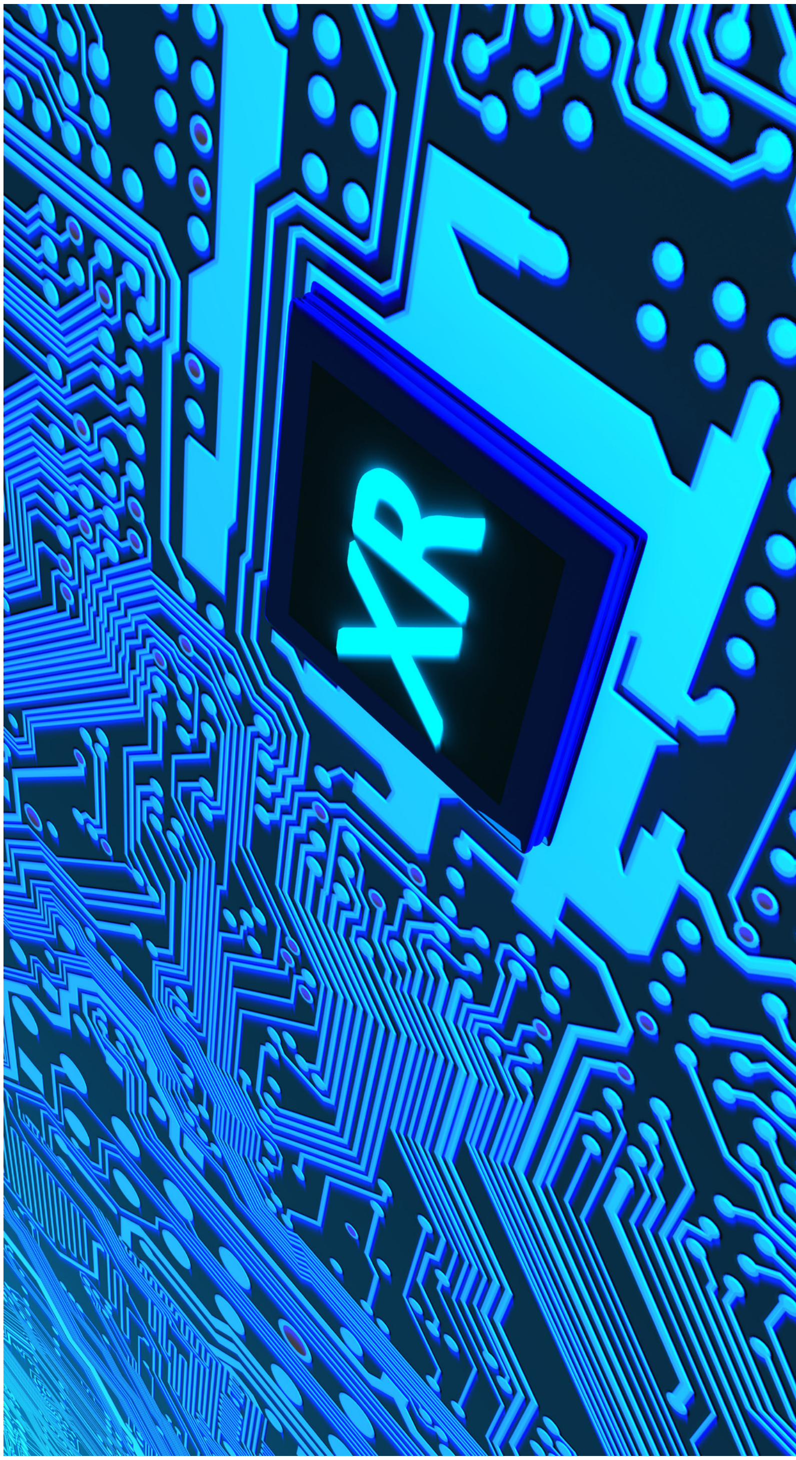
3 XR REQUIREMENTS

Multisensory XR applications have a unique set of requirements that includes bounded low latency and high uplink (UL) and downlink (DL) bandwidth. These are challenging requirements due to scale and mobility at various rates of speed (e.g., walking, driving, fast trains) as well as coverage and handovers.

The Next G Alliance (NGA) ***6G Applications and Use Cases*** report [2] identified Multisensory XR as one of the key four areas. Section 7 of the NGA report provides detailed information on requirements and characteristics that cover performance, localization and sensing, connectivity, communication, services, and device aspects of XR applications.

XR covers a very large spectrum of use cases. Although every use case can be different, each use case category has its own general set of characteristics. The following provides an overview of the range of values for different categories of XR use cases:

- UL and DL range: holographic communication (1 Gbps) to gaming (50 Mbps)
- Latency UL and DL: mission critical (<1 ms) to gaming and entertainment (<20 ms), education (<50 ms)
- Jitter: mission critical (microseconds), otherwise (milliseconds)
- Mobility: bullet trains (500 km/h) to pedestrian speed
- Availability: mission critical (99.9999%) to entertainment (99.9%)
- Position accuracy: industrial (1 mm) to entertainment (1 m)
- Connectivity surviving time: mission critical (microseconds) to gaming and entertainment (milliseconds)



4 CURRENT STATUS OF XR

A new wave of AR and VR began in 2016 when the Oculus Rift and HTC Vive products were released. Newer systems such as Microsoft Mixed Reality, Oculus Go, and HTC Vive Focus have since progressed to enable true mobility. All these systems use some form of visual-inertial fusion to achieve a level of latency that remains relatively unnoticeable to humans.

Many commercially available head-mounted displays (HMD) with high resolution and performance are currently beyond the means of the average consumer. They are also too heavy for day-long use and lack enough battery power for extended use. This has inspired a few companies to develop lightweight XR glasses with a similar field of view and performance that could be tethered to smartphones for connectivity and local processing. Demand for small form factors, fashionable standalone devices, and longer battery life has ignited the need for offloading XR processing to the edge. This offloading brings forward several complex challenges as applications must seamlessly communicate with the network via standard APIs to assess available network resources and viable edge sites with adequate resources that can execute different offloading strategies.

Affordability remains a challenge, motivating some service providers (e.g., CSPs in South Korea [3]) to subsidize the cost of a new generation of lightweight AR glasses for consumers. Not as constrained by cost, enterprises are emerging as a fertile environment for development and deployment of XR applications [4]. The enterprise sector can enable specific XR applications that significantly help reduce cost, improve quality, and time to market. Enterprises use VR for training and other niche use cases. Enterprise AR users can naturally interact with the physical environment with the overlay information to improve their performance. There is also substantial interest in using XR technology in various verticals [5]. However, many of the key enablers — such as scale, quality of experience, end-to-end ecosystem, and cost-effective solutions — are still under vigorous research and in early development.

Integration presents another challenge. There are many silos of XR technology advancements and very few end-to-end collaborations. There is a need for device vendors, network infrastructure providers, network application programming interface providers, hyperscale cloud providers, game engine developers, and application developers to work together cohesively to develop a scalable blueprint for XR.

4.1 The Physiological Effects of XR

Humans perceive their orientation and self-motion through various sensory organs. The information from the vestibular (for a sense of balance and spatial orientation), visual, inner ear receptors, and proprioceptive senses (for body awareness) acquire a coherent perception of self-motion, location, and action in a three-dimensional space. The main sensory systems involved in postural control and balance are the visual, vestibular, and somatosensory (touch or tactile perception) systems.

In the environment provided by the VR headset, latency in visual feedback has a strong influence on haptic task performance (e.g., operating a crane or playing an esport). High latency in immersive experiences may induce sickness and dizziness [6] for some users, making the application uncomfortable or unusable for those impacted.

4.2 XR Requirements and Architectures

The system requirements for providing immersive XR experiences to users [7] could include:

1. Significant graphics processing power to drive high-resolution, high-fidelity graphics at high and consistent frames per second rates of 60-90 today and can expect 90-120 in 6G timeline for near real-time creation of environment map, localizing UE position in that map, and pose-graph optimization.
2. Accurate tracking of the user's movement and quickly updating the image in the user's viewport to reflect that movement, thus creating the illusion that the user is immersed in a virtual or augmented environment.
3. Lightweight, non-intrusive, low-power, ergonomic user equipment. These requirements are driven by an expectation of a user-friendly reading-glass form factor, a limited battery size possible on such form factors, and an expectation of long-duration, comfortable wearability.

The time difference between the user's movement until the corresponding image is displayed to the user is referred to as "motion-to-render-to-photon." This is different from "motion-to-photon," where simple movement may be reflected on the display screen via techniques such as asynchronous time warping or space warping [3] on an existing image to smooth out the motion before the newly rendered frame is displayed.

XR applications can be delivered via different underlying multimedia architectures [7] with different choices of distribution of computation, media formats, media processing requirements, and use of 5G and other wireless systems. Different architectures offer different balances between various end user needs or device requirements and overall user experience. For instance, a device-based architecture has XR-related computation predominantly on the device. Split-XR compute architecture divides the computation between an edge server and the device, leveraging computing power from edge compute servers for graphics rendering and other complex computing tasks that may require a large dataset (e.g., object recognition). This requires an edge server to be kept up to date continuously with the pose and motion of the users (and/or their hands and controllers). The graphic frame buffer is transported over a low-latency communications link such as 5G to the user device (e.g., lightweight glasses) to be displayed [8] on screen.

Given that the render operation is performed on the edge server, the motion-to-render-to-photon metric is a function of the network latency, as well as the edge server-side and device-side compute latencies. This architecture results in high-throughput, low-latency, and high-reliability traffic requirements on the underlying wireless system between the device and the edge server. XR lightweight glasses are expected to have a total power consumption of under 3 watts. The low-power requirement on XR devices translates into 5G modem and radio-frequency front-end (RFFE) power requirements that can be on average less than 0.5 W, which is much lower than that on a smartphone. The XR lightweight glasses are also expected to require low-power sensors, cameras, and microphones, and on-device processing, which are supported by state-of-the-art purpose-built system-on-chip AR platforms like Snapdragon AR2 Gen1 [9].

5G supports solutions based on both split-XR and device-based architectures. As XR devices move to more user-friendly form factors, it limits the compute power due to thermal constraints and imposes the need to access low-latency edge compute. As XR experiences move from single-user cases to multi-user collaborative and social experiences, it requires access to server-based 3D content, 5G, and next-generation wireless technologies, all of which will play an even more prominent role in delivering the required end-to-end experience. The evolution of the 5G system and next-generation wireless technologies is anticipated to be driven by the more stringent requirements imposed by the split-XR compute architecture. Standardization bodies such as 3GPP [10], IETF [11], and MPEG-I [12], and industrial forums such as Open-XR [13], VR-IF [14], DASH-IF [15], and Metaverse Standard Forum [16] are enabling industries worldwide to harmonize standardization, common networking abstractions, and interfaces to ensure ease of multivendor interoperability and an open multisource solution ecosystem.

4.3 5G Evolution for XR

It is anticipated that XR glasses will continue to evolve with lower power requirements and more immersive applications requiring higher data rates. A 3GPP study in Release 17 [17] recognized the need for further enhancements to the 5G system. 3GPP Release 18 promises to significantly improve support for higher data rates and capacity while also introducing power and latency reduction techniques to enable more immersive AR experiences. The potential enhancements in 3GPP Release 18 span activity in the System Architecture and Service working group (SA2) and Radio Access Network (RAN) working group and can be grouped into three categories.

The first is the introduction of application awareness to 5G systems, and enhancements to the Quality of Service (QoS) and power framework. Current 5G systems define transport requirements on IP packets, with no detailed view of the XR traffic attributes. 3GPP Release 18 [18] is expected to standardize schemes for attributes of XR traffic bursts — including burst periodicity and jitter, burst start and end time, and burst data units — to be conveyed to the 5G system, which uses the information to optimize power-saving algorithms and provide QoS directly based on requirements on burst data units.

Another set of proposals strives to lower device power consumption by adapting existing 5G power-saving mechanisms like Connected Mode Discontinuous Reception (CDRX) to XR traffic. In particular, the cadence of CDRX cycles will have to be enhanced to match the cadence of XR traffic to maximize power savings. A third set of proposals aims to increase 5G system capacity to handle multiple simultaneous XR traffic sessions. Although XR traffic requires low latency, overlapping arrival of XR traffic among different UEs will require sharing of 5G radio resources, limiting the number of simultaneous sessions. A minimum viable capacity is key to the successful launch and scaling of XR services on 5G systems.

Beyond Release 18, 3GPP's Services (SA1) working group is defining requirements for new and enhanced services, features, and capabilities that other 3GPP Working Groups will further develop in their Release 19 workplan. SA1 has a "Study on Localized Mobile Metaverse Services" to define 5G system requirements to support shared interactive and immersive metaverse user experiences, accessed locally or remotely. Some key aspects include identification of users and their digital representations (avatars), acquisition of local (physical and digital 3D) information, and exposure of such information to third parties to enable metaverse services. SA1 also has a "Study on Integrated Sensing and Communication" defining requirements on 5G system to provide integrated communication and sensing services addressing different verticals. Key aspects include identification of potential service requirements on collection and reporting of the sensing measurement data and the exposure of the sensing capabilities and information to third parties.

5 NEXT-GENERATION VISION

In 2030, society will have been shaped by 5G for 10 years. Multisensory communication increased holographic representation, digital twins, lightweight wearable haptics, brain-computer interfaces, and an internet of senses will be among many norm-changing applications supported on 5G. However, many of these same applications are considered as fundamental 6G use cases. So, what is the difference?

The following are some of the 6G differentiators that will significantly improve the adoption rate of 5G applications, deployment scale, performance, and quality of experience. They will also usher in this new era of futuristic applications and use cases that today are only in the realm of our imaginations.

> **Scale and Connectivity:** The allocation of 6G spectrum will play a crucial role in unleashing many of the above use cases at scale.

> > Lower centimeter wave bands will be needed for wide-area coverage of future 6G services, while millimeter wave bands can support extreme data rates. Suitable combinations of frequency bands will be important to support 6G advanced applications at scale.

> > The significant increase in 6G data rates will enable at-scale deployments of advanced services such as immersive reality, holographic communication, photorealistic avatars, haptic communications, remote operations, and the internet of senses.

> **Cognitive Networks:** Networks will gradually become cognitive systems with the ability to sense, reason, acquire new knowledge, and act autonomously. They will be fully controlled by intent-based technologies, while humans can focus on defining services and setting operational goals to fulfill business objectives. The key enablers for this evolution will be data-driven operations, distributed intelligence, continuous learning, intent-based automation, and explainable and trustworthy AI. Moreover, all these technologies must work in synergy across different functional architectures and deployment scenarios and be capable of supporting different business models.

> **Distributed Compute Fabric:** 6G will further flatten networks, compute, and storage capabilities. In the future, applications can be run from anywhere (e.g., close to the users or across the globe, depending on need). They can also take different forms (e.g., computing can be distributed across the network in the user device, central clouds, or multi-clouds).

> **Sensing Capabilities:** Including sensing capabilities in a communication network is a very promising area. For instance, it enables exciting new use cases where spatial sensing can be offered as a service to users or applications that are external to the network. The ability to infuse senses and transmit them in a manner that is authentic to the human mind will open the doors to new, fascinating sets of applications and use cases. Sensing-as-a-service has been identified as a novel feature of 6G systems.

> **APIs:** In the 6G ecosystem, the industry will also see a much stronger push toward platform thinking where developers and software integrators can natively interact with the network to configure it to the applications' needs in real-time. In addition, there will also be the emergence of network APIs, which will be of enormous use for human and machine applications in consumer and industry markets.

> **Energy Efficiency:** One of the global goals for 6G networks is to significantly improve energy efficiency. Many companies are actively working to enable a future with zero-energy devices and carbon-neutral networks.

5.1 Education and Training with XR

Advanced technologies such as XR offer promising solutions for future education and training by delivering high-quality education services for both remote and in-person settings [19]. This includes immersive classrooms with avatar-based instructors, support for remote students, and AR/VR content with holograms that replace traditional teaching tools.

Digital twin technology provides students with the opportunity to work with digital replicas of real-world objects, letting them make mistakes in a risk-free environment, which is attractive for high-risk environments (e.g., medical, power production).

In "The Future Healthcare Journal," a paper [20] concluded that XR technologies have unique attributes that improve learning outcomes. XR brings the advantage of high-fidelity simulators (e.g., tracking level, frames per second, field of view, etc.) to the complexities of medical education. The higher levels of interactivity in domains like anatomy, ultrasound scanning, and surgical simulators improve understanding, while the variety of unique XR modalities — such as tactile inputs — helps elevate the support of the instructional objectives.

6G can be leveraged to improve educational opportunities for disadvantaged communities. People who lack access to traditional educational facilities due to physical handicaps or other challenges will also benefit from 6G-enabled education and training programs. For this to be realized, multisensory XR education requires universal access to XR devices (e.g., AR/VR HMDs, hologram receivers, handheld sensors), high-speed and highly reliable networks, and educational content.

5.2 Entertainment with XR

The entertainment industry has been the driving force of XR applications and device development for many years. Multisensory XR creates opportunities for the next set of consumer experiences and is already gaining traction with the 5G connectivity. In the 6G era, families could experience the interactive and more thrilling rides at home instead of incurring the costs and inconveniences of travel to the theme parks, which would also contribute to a greener society. Through immersive sensory feedback (e.g., through haptics sensors and responders with 6 Degree-of-Freedom (6DoF) and 360° 8K video view), people could experience events like the moon landing. Instead of just viewing it on a flat screen, they could feel the temperature changes and the soil texture and view Earth back from the moon.

Advances in the devices, such as AR glasses or HMDs, are critical for reaching a wider audience/market for XR experiences. Initially, it is expected that these devices will be use-case specific; however, with the advancement of display technologies and more interactive use cases, more general-purpose devices can be expected. Also, research is needed in multisensory integration to enable production of lightweight, inexpensive, energy-efficient wearable devices that are comfortable for long-term use. Haptic-rendering algorithms need refinement to help users determine the magnitude and location of the forces exerted on their XR device. Combining the sense of touch with the visual perception of the object and any audible cues would convince the brain that this object exists in the virtual world.

5.3 Health Care with XR

XR telemedicine has the potential to provide more affordable medical services to underserved communities by providing high-quality remote access to skilled specialists and reducing the need for patient travel for medical care. XR telemedicine may also increase accessibility for patients with difficulties (e.g., elderly, mobility challenged) obtaining medical services, regardless of availability of those services.

Figure 5.3 Remote-Assisted Procedure

XR telepresence capabilities can be leveraged for the medical community to expand telemedicine appointments and consultations, thus increasing the effectiveness and equity of public health services to ensure healthy lives, increase longevity, and improve quality of life.

By monitoring real-time patient behavior patterns, XR and AI can create safe, remote care for patients while also reducing providers' operational costs. Some specific examples are:

- VR could help visually impaired patients attain some level of vision. Research is ongoing to help translate images of the patient's surroundings into audio communications to help them lead their lives independently and safely. For patients whose visual impairment is due to retinal damage, research is underway where a VR headset may act as their artificial eyes.
- In-body subnetworks — made by devices either on the surface (e.g., wearables, skin patches, or sensors) or implanted within (e.g., pacemakers or insulin pumps) — provide more immediate and accurate data. 6G networks may enable new applications for wearables and implanted devices. For example, 6G networks could consolidate data from the patients' devices for timely action (especially in life-critical scenarios) by health care providers on a real-time basis through the use of AI and edge computation. 6G networks can also enable the control of exoskeletons as an ambulatory aid for the disabled.
- Applications like remote robotic surgery will need to integrate 3D imaging with haptics while providing highly reliable and dependable services. It is anticipated that 6G will allow for the implementation of such applications through XR, offering more immersive experiences for surgeons.

Robust coverage and accessibility are key elements of XR services. They enable full mobility of the users, indoors and outdoors, thus ensuring the full potential that XR services hold for improving lives in society at large.

6 SOCIAL AND ECONOMIC IMPACTS

6.1 Supporting UN Sustainable Goals

6G networks will not only support commercial endeavors, but also XR, whose versatility can be leveraged to address societal and economic needs. Figure 6.1 illustrates the UN Sustainable Development Goals (SDG) [21], which XR can help achieve. Some examples are:

> Ensure healthy lives and promote well-being for all at all ages (SDG #3) – see Section 4.3 for more details.

> Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all (SDG #4) – see Section 4.1 for more details.

> Empower all women and girls to achieve gender equality (SDG#5). SDG #5 is expanded to be all inclusive to all individuals.

> Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation (SDG #9)

Figure 6.1 UN Sustainability Goals [22]

6G networks supporting immersive education contribute to providing high-quality education to all students, regardless of their location, age, or gender. When widely available, remote learning can develop a skilled workforce, leading to an increase in work productivity, ultimately resulting to increased economic growth. XR can facilitate competition and help attain broader markets for small and disadvantaged businesses.

6.2 Economic

The impact of 6G XR on the global transportation industry may be significant. As many companies look to reduce their carbon footprint, a robust and mature XR capability may replace in-person meetings and conferences. Sightseeing vacations may become virtual. XR could be a significant effort to mitigate, if not reverse, climate change, but job reductions across the transportation, travel, and convention industries may be the tradeoff cost.

6.3 Societal

During the pandemic, people were challenged by social isolation from working and learning from home. Although 5G brought us numerous collaboration and communications applications and services, 6G's XR applications can take that to the next level as virtualized interactions will become more realistic social interactions. Although XR may replace some face-to-face human interactions, it also brings a possibility of enriching human interactions and reducing social isolation for others.

6.4 Legal and Ethical Considerations

Conversations about many of multisensory XR's legal and ethical considerations should begin now to ensure that appropriate security and privacy mechanisms are designed into the developing XR ecosystem. XR will generate, store, and transmit very personal and sensitive data, including unconscious responses to stimuli (e.g., eye tracking), that may be collected and used without the user even being aware [23]. This expansion of personal information collection is essential for the AI/ML-based functions that many XR use cases require and may also include renderings of physical likeness and identity.

Informed consent for people who are legally unable to provide consent (e.g., children) is another area of concern applicable to XR. Pre-XR, society seems unable to fully protect children from online bullies and predators. The multisensory aspect of XR increases potential dangers (e.g., haptically augmented assault and battery).

6.5
Privacy and Security in XR

Advancements in XR introduce several critical privacy and security concerns. Examples include leakage of sensitive environmental and sensory information used in immersive interactions, the ability for bystanders in immersive experiences to consent to the use of their likeness in XR interactions, the safety and integrity risks of sensory manipulation in interactive experiences, and the substantial tradeoffs in privacy, security, and efficiency that come with combatting these threats. In response to these concerns, next-generation wireless innovation must build on existing safeguards present in the 5G system to continue to balance practical privacy and security solutions with restrictive latency and performance requirements necessary to sustain rich immersive XR experiences. Advances in 6G will allow XR applications to move from primarily wired connections on home hardware into the ubiquitous and distributed mobile experiences enabled by Next G technology. As a result, maintaining and expanding upon the mobile network infrastructure's privacy and security protections will be critical to facilitate consumer trust and build scalable markets in the multisensory XR domain.

7 NEXT STEPS: WHAT NEEDS TO BE DONE TO PROGRESS XR

7.1 Research Recommendations

The research topics for improving XR services can be focused on the following areas:

> **Devices and human-machine interfaces** are lightweight wearable devices or means, such as holographic displays, to project images and accept input.

> **Open interfaces and configurable APIs** ensure adaptability of the network toward applications and effective network resource management. This work includes enabling a global development community to create the next generation of network-aware applications and services.

> **Multi-level Quality of Experience (QoE)** allows applications to be presented in acceptable service levels according to the levels of network resource availability (e.g., use image compression and data compression to reduce multi-sensory data size to reduce network transmission bandwidth within allowable latency).

> **User data protection** provides security and privacy protection for users in the AI/ML era.

> **Adaptative processing and rendering** of new/existing media formats addresses synchronization and data compression requirements to accommodate available network bandwidth.

Image data compression is an important issue for XR. Delivering high-fidelity, interactive, immersive multimedia content is a challenge and may require terabit bandwidth to transmit, as stated in the "Drone Racing" use case [2]. Today, a powerful video compression technology (e.g., the Versatile Video Coding (VVC) in ITU-T/IEC H.266 [24]) can help reduce data size and make some applications feasible in a 5G environment. Nevertheless, it will require more advanced 3D image data compression schemes as addressed in the "beyond HEVC discussions" [25] to ensure adequate QoE for visual effects in the 6G era. For next-generation XR applications, richer visual content and multisensory experiences will require larger bandwidth, higher robustness, and lower latency – even more so in immersive lifelike VR applications, where meeting user expectations for experience and avoiding uncanny valley effects is essential. The importance of a powerful data compression technology cannot be overemphasized.

7.2 Potential Government Activities

7.2.1 Research Funding and Incentives

The U.S. cannot afford to lag other nations that pose threats to its national security and economic welfare. The government is committed to advancing 6G for a multitude of technical and societal reasons.

Other countries have already made significant commitments to 6G research, so to achieve the government's goal for North American leadership, critical research and investment must begin now. Congressional support is needed to ensure that the most innovative research continues to take place in the US and elsewhere in North America.

Full funding of these research programs — particularly the NIST and NSF research authorized by the CHIPS and Science Act [26] — is critical to the nation's long-term economic and national security.

7.2.2 Regulations and Policies

Technology develops faster than government regulations, and XR will be no different. Government, industry, and academia should begin and continue dialogs to ensure that XR applications are developed to address legal and ethical issues, thus ensuring consumer safety, privacy, security, and trust.

Government agencies with oversight of security and privacy should continue to expand guidance and guidelines for XR uses and technologies. The threat of deepfakes, which are false media content created by manipulating existing images or videos, is extendable to the world of XR.

Sufficient commercial spectrum and efficient spectrum use are necessary enablers for XR to mature, scale, and live up to market expectations. Policymakers will be addressing 6G spectrum through 2030, and any delays to initial 6G commercial deployments should be minimized.

8 CONCLUSIONS

This paper explores the promise of XR and identifies its potential to improve quality of life in the workplace and the home. Although XR is still in the early stage of development, it already demonstrates profound potential to greatly impact humanity and the global marketplace.

To successfully leverage XR's potential, advances are needed in several supporting technical areas (e.g., device and human-machine interfaces, user data protection, adaptive processing and rendering, data compression). Telecommunications networks also will need to be enhanced to support the increased demand of connectivity and bandwidth. To facilitate the acceptance of XR into everyday life, ethical considerations, policy, and legal aspects all need to be addressed to mitigate risks to security and privacy.

9

ABBREVIATIONS AND ACRONYMS

6DoF .... 6 Degree-of-Freedom
AI .... Artificial Intelligence
API .... Application Programming Interface
AR .... Augmented Reality
CDRX .... Connected Mode Discontinuous Reception
CSP .... Communications Service Provider
DASH .... Dynamic Adaptive Streaming over HTTP
HD .... High Definition
HMD .... Head Mounted Display
ICT .... Information and Communications Technologies
IEC .... International Electrotechnical Commission
IF .... Industry Forum
ISO .... International Organization for Standardization
JVET .... Joint Video Experts Team
NGA .... Next Generation Alliance
PDU .... Protocol Data Unit
PTSD .... Post-traumatic Stress-Disorder
QoE .... Quality of Experience
QoS .... Quality of Service
RFFE .... Radio Frequency Front End
SDG .... Sustainable Development Goals
UE .... User Equipment
UN .... United Nations

10 REFERENCES

1. BCI Technology: How does a Brain-Computer Interface Work? (2019) Techslang. https://www.techslang.com/how-does-a-brain-computer-interface-work/

2. Next G Alliance, 6G Applications and Use Cases, https://www.nextgalliance.org/white_papers/6g-applications-and-use-cases/

3. Nreal Light AR glasses add VR lenses, launch August 21 in South Korea, (2020). https://venturebeat.com/business/nreal-light-ar-glasses-add-vr-lenses-launch-august-21-in-south-korea/

4. Fink, C. (n.d.). Five Enterprise XR Lessons From Lockheed. Forbes. https://www.forbes.com/sites/charliefink/2019/10/24/five-enterprise-xr-lessons-from-lockheed/?sh=5252ec9b19b2

5. Use Cases and Industries. XR Collaboration. https://xrcollaboration.com/guide/a-global-resource-guide-to-xr-collaboration/use-cases-and-industries

6. Motion Sickness in VR: Why it happens and how to minimise it. https://virtualspeech.com/blog/motion-sickness-vr#:~:text=The%20body's%20sense%20of%20balance,work%20harder%20to%20be%20orientated

7. 3GPP TR 26.928, "Extended Reality (XR) in 5G"

8. 3GPP TR 26.998, "Support of 5G glass-type Augmented Reality / Mixed Reality (AR/MR) devices"

9. Qualcomm Launches Snapdragon AR2 Designed to Revolutionize AR Glass-es. https://www.qualcomm.com/news/releases/2022/11/qualcomm-launches-snapdragon-ar2-designed-to-revolutionize-ar-gl

10. 3GPP – The Mobile Broadband Standard Partnership Project. https://www.3gpp.org

11. https://www.ietf.org

12. MPEG-I | MPEG. https://mpeg.chiariglione.org/standards/mpeg-i

13. OpenXR - High-performance access to AR and VR —collectively known as XR— platforms and devices. The Khronos .https://www.khronos.org/openxr

14. https://www.vr-if.org/

15. DASH Industry Forum | Catalyzing the adoption of MPEG-DASH. https://dashif.org

16. Metaverse Standards Forum. https://metaverse-standards.org

17. 3GPP TR 38.838, "Study on XR (Extended Reality) evaluations for NR"

18. 3GPP TR 23.700-60, "Study on XR (extended reality) and media services"

19. Goldberg, Suzanne B. "Education in a pandemic: the disparate impacts of COVID-19 on America's students." USA: Department of Education (2021)

20. Logeswaran A, Munsch C, Chong YJ, Ralph N, McCrossnan J. The role of extended reali-ty technology in healthcare education: Towards a learner-centred approach. Future Healthc J. 2021 Mar;8(1):e79-e84. doi: 10.7861/fhj.2020-0112. PMID: 33791482; PMCID: PMC8004346. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8004346/#:~:text=XR%20technologies%20such%20as%20virtual,learning%20at%20a%20lower%20cost

21. United Nations. (2023). The 17 Sustainable Development Goals. https://sdgs.un.org/goals

22. United Nations. (2018). Communications materials - United Nations Sustainable Devel-opment. United Nations Sustainable Development. https://www.un.org/sustainabledevelopment/news/communications-material/

23. Bernard Marr, 5 Problems And Solutions Of Adopting Extended Reality Technologies Like VR And AR, June 18, 2021, https://www.forbes.com/sites/bernardmarr/2021/06/18/5-problems-and-solutions-of-adopting-extended-reality-technologies-like-vr-and-ar/?sh=2b147143f239

24. https://www.itu.int/rec/T-REC-H.266-202204-I/en

25. Y. Ye, J. M. Boyce, P. Hanhart, "Omnidirectional 360° Video Coding Technology in Re-sponses to the Joint Call for Proposals on Video Compression with Capability Beyond HEVC," IEEE Trans. Circuits Syst. Video Technol, Vol. 30, No. 5, MAY 2020

26. P.L. 117-167 § 10230 et seq., https://www.govinfo.gov/link/plaw/117/public/167?link-type=pdf&.pdf

9.1
Additional References

Motion to Photon Latency in Mobile AR and VR
https://medium.com/@DAQRI/motion-to-photon-latency-in-mobile-ar-and-vr-99f82c480926

Proprioceptive accuracy in Immersive Virtual Reality: A developmental perspective
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6992210

J.M.P. van Waveren, "The Asynchronous Time Warp for Virtual Reality on Consumer Hardware," 22nd ACM Conference on Virtual Reality Software and Technology, 2016

G. S. Sawicki, O. N. Beck, I. Kang, and A. J. Young, "The exoskeleton expansion: improving walking and running economy," BioMed Central Journal of Neuro-engineering and Rehabilitation, vol. 17, no. 1, pp. 1–9, 2020

What the North American Next G Alliance means for 6G https://www.ericsson.com/en/blog/2022/6/north-american-next-g-alliance-6g

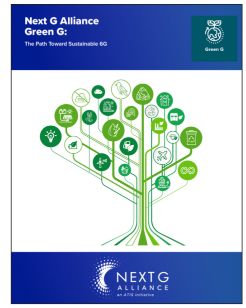
3GPP specification Release 15, 3rd Generation Partnership Project (3GPP). [Online]. Available at http://www.3gpp.org/release-15

NEXT G ALLIANCE REPORTS

6G Technologies

6G Applications and Use Cases

Roadmap to 6G



Green G: The Path Toward Sustainable 6G

6G Distributed Cloud and Communications System

Trust, Security, and Resilience for 6G Systems

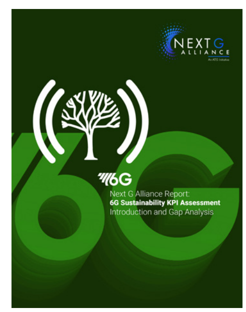
Digital World Experiences

Cost-Efficient Solutions

Sustainable 6G Connectivity — A Powerful Means of Doing Good

Next G Alliance Report: Terminology for Frequency Ranges

Next G Alliance Report: Multi-Sensory Extended Reality (XR) in 6G



Next G Alliance Report: 6G Sustainability KPI Assessment Introduction and Gap Analysis

6G Market Development: A North American Perspective

Building the foundation for
North American leadership in
6G and beyond.

nextgalliance.org

NEXT G ALLIANCE

An ATIS Initiative