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6G Immersive Data Sharing

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Capacity Analysis of Use Cases for Department of Defense

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Abstract

Sixth generation (6G) cellular service promises hyper-connectivity of humans and environment through always-on, sub-millisecond, ubiquitous access. Truly unique 6G use cases include integrated space-air-ground networks for global command and control, full thing-to-thing artificial intelligence–enabled communications for machine autonomy, and immersive extended reality experiences. 6G is a decade away, and there are many challenges to realizing 6G as a technology before we even think about deployment. Assuming we clear those hurdles, what is the “art of the possible” with 6G that cannot be realized with current mobile technology? This paper explores the innovative, immersive data-sharing experiences that will be made possible through ubiquitous connectivity that resonate with both national security and public sector use cases. We build an argument for U.S. leadership in 6G standards definition and technology innovation. We provide a definition of immersive data sharing and the reasons fifth generation technology alone will not be enough. We highlight current research and future application ideas. Finally, we provide recommendations for 6G research and investment to forward U.S. leadership in this strategic technology.

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Executive Summary

Sixth generation (6G) cellular service promises hyper-connectivity of humans and environment through always-on, sub-millisecond, ubiquitous access. Truly unique 6G use cases include integrated space-air-ground networks for global command and control, full thing-to-thing artificial intelligence–enabled communications for machine autonomy, and immersive extended reality experiences. Standards bodies have not yet formally defined specifications for 6G cellular services, yet academia, corporations, and countries are investing in research toward 6G technologies and services.

Each successive generation of mobile access has focused on extending network performance toward higher bandwidth, lower latency, and better reliability. Current fifth generation (5G) technology presents network configuration trade-offs on latency, energy, throughput, and end-to-end reliability to achieve optimum performance for particular application requirements. 5G alone will not be able to support the increased demand for the ultra-dense deployment of devices and connectivity envisioned for 6G use cases. 6G will be designed to address additional requirements, including global coverage, spectral efficiency, lower carbon footprint, and embedded network intelligence. But the enhanced design comes at a price. Studies estimate between $30 and 150 billion is required over the next decade to ensure 5G access for Americans as well as provide the backhaul broadband infrastructure to support planned 5G rollouts. This does not even consider the additional equipment and infrastructure required for 6G—and these studies cite numbers for the U.S. only. Increasing access through cellular technology has contributed significantly to global economic growth; however, network infrastructure has very high fixed costs, so unless new business models can be realized, 6G deployment may be greatly affected by economies of scale.

Government leadership and policy can play a positive role in offsetting the commercial investment required to deploy, upgrade, and manage network infrastructure. The U.S. Congress is currently debating a few bills to bolster support for telecommunications research and a 6G task force. However, given the slow U.S. approach to 5G, some industry insiders have doubts about the country's ability to keep pace with China and perceive a general lack of U.S. resolve in 6G research and development.

Assuming technical limitations and deployment economics can be solved, what is the "art of the possible" with applications—particularly immersive data sharing—over 6G networks? We define immersive data sharing as building interactions for collective participants in a combined experience that dramatically increases the efficacy of the encounter's purpose while maintaining loose requirements on physical assets and proximity. Potential use cases include immersive experiences in the augmented and virtual reality (AR/VR) space and digital twin—computer models coupled to real world objects. Immersive experiences are made possible through new video delivery formats that substantially increase the throughput required for data delivery to headsets for rendering. The latency required for these immersive formats is greatly reduced from milliseconds to sub-milliseconds to facilitate the near-real-time motion tracking required for the immersive experience. Digital twin may also make use of these immersive video formats in addition to live sensor data, to synchronize the digital twin with the real-world instance it is modeling.

The potential use cases for Department of Defense applications are compelling. Synthetic Training Environment Live Training System (STE-LTS) is an immersive AR/VR experience being developed to support soldier training; it converges today's live, virtual, constructive, and gaming environments into one common synthetic environment. STE will enable more realistic and complex training environments that reflect potential operations and future conflicts with adversaries. The initial scale of these simulations is intended to cover platoon-scale (20–50 soldiers) engagements, but future plans aspire to support battalion-scale (400–1,200 soldiers) engagements over large outdoor areas. This scaling will require immense throughput, near-zero latency, and sophisticated and efficient headsets not yet available.

Digital twin technology will also bring advancements in maintenance and safety while reducing overall operational costs of physical deployed systems. More than just a three-dimensional computer-aided design model, digital twin links sensors from physical objects to the digital instantiation, allowing near-real-time analysis of operating metrics as well as extrapolating future duty cycles to diagnose potential issues and faults. Predictive maintenance and improvements to field repair speed and efficacy are among the benefits of digital twin technology for soldiers in the field.

As we look to a future that includes 6G technology, we see tremendous opportunities for immersive data-sharing applications to push far beyond current capabilities and limitations and provide truly data-rich, immersive experiences for multiple distributed users at scale. Beyond niche gimmicks and monetized commercial use, these immersive experiences can provide impact to both national security and public sector use cases. However, substantial investment must be made to fund both the research and development and the infrastructure upgrades required to realize 6G technology. In addition, beyond the network, there is opportunity for innovation in the applications that will run on 6G-enabled networks. Advancements in AR/VR rending software, video delivery, and user endpoints—including headsets, three-dimensional displays, and human-machine haptic interfaces—are all areas to target research and investment.

While 6G deployment may still be a decade away, research and investment must start now to establish leadership in this strategic technology. We recommend:

From a policy perspective, engage in the Third Generation Partnership Project to define specifications for 6G networks, create legislation to incentivize research and development, and continue the ban on untrusted foreign equipment manufacturers.

From a network perspective, invest in domestic backhaul infrastructure and partner with service providers to develop new business models and incentives for underserved rural markets.

From a technology perspective, unleash a new spectrum for radio access and wireless backhaul, fund research and development in proposed 6G technologies, and explore opportunities in over-the-top immersive data-sharing hardware, software, and application services.

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1 Introduction

Cellular communications networks are defined by their generation number ranging from first generation (1G), which introduced mobile voice in the 1980s, through third generation (3G), which included the first mobile web services at the turn of the millennium. Today, fourth generation (4G) services offering true mobile internet are in wide use, and 5G services are defined and in deployment offering faster speeds, higher connection densities, and new application possibilities.

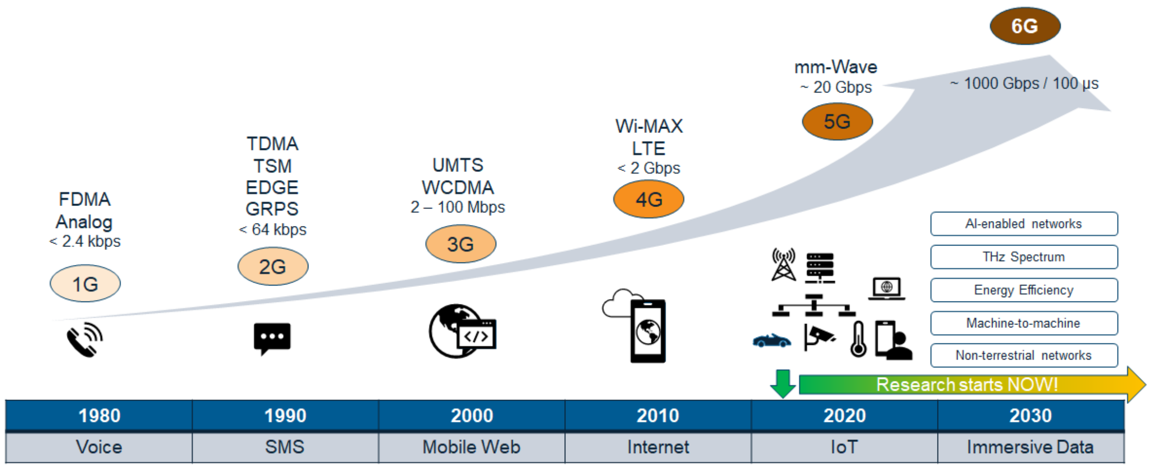

Figure 1-1: Cellular Communications Network Evolution [1]

Although standards bodies have not yet formally defined specifications for the next generation of cellular services, academia,[1] corporations,[2,3] and countries[4,5] are investing in research toward sixth generation (6G) services. 6G promises hyper-connectivity of humans and environment through always-on, sub-millisecond, ubiquitous access. The immersive data sharing that 6G will enable creates an innovation space for visionary services and experiences. Truly unique 6G use cases of interest to Department of Defense (DoD) include integrated space-air-ground networks for global command and control, full thing-to-thing artificial intelligence (AI)-enabled communications for machine autonomy, and immersive extended reality experiences. However, significant technical and economic challenges must be overcome to realize 6G technology.

Research and investment in 6G at this early stage will define the art of the possible and drive specification development. Those who act now will have the experimental knowledge afforded to the first movers and can drive architecture standards and future prototype pilot deployments. And because development, deployment, and adoption cycles span multiple decades, those who act now could be positioned to lead well into the 2040s.

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[1] https://ieeetv.ieee.org/channels/communications/6g-academic-research-around-the-globe-panel-discussion-2021-b6gs
[2] https://www.huawei.com/en/technology-insights/future-technologies/6g-white-paper
[3] https://www.nokia.com/about-us/newsroom/articles/nokias-vision-for-the-6g-era/
[4] https://nextgalliance.org/working_group/national-6g-roadmap/
[5] http://www.caict.ac.cn/english/news/202106/P020210608349616163475.pdf

The estimated global economic output [2], [3] attributed to mobile communications is over one trillion U.S. dollars; therefore, securing innovations and patents and leading architecture and specification development are essential steps to harnessing the truly global reach 6G will enable through non-terrestrial networks and global ubiquitous connectivity. The recent U.S. defensive posture toward blocking 5G competition will not serve the U.S. well in the emerging, competitive 6G leadership race. The U.S. government must rank 6G communication services as a national strategic initiative and invest appropriately.

1.1 Scope

MITRE Technology Futures innovation area has funded a portfolio of 6G research to tackle technological, architectural, and environmental challenges in realizing 6G standards and deployment. The scope of this paper is to explore and identify truly unique 6G services and experiences that resonate with DoD use cases and to argue for thought leadership and strategic policy initiatives to incentivize technology development.

1.2 Background

In the late 1990s, cellular communication was taking off globally, and the concept of an Internet Protocol (IP)-based “cell-web” was forming. International standards did not yet exist, and global roaming needed to be addressed. AT&T and Nortel Networks partnered to propose and develop solutions for wireless internet, launching a global initiative that attracted interest from several global telecom companies. In December 1998, the Third Generation Partnership Project (3GPP) officially formed when the European Telecommunications Standards Institute (ETSI) took notice of the international standards efforts and partnered with other standards and telecom organizations to develop the next generation 3G cellular networks based on Global System for Mobile Communications (GSM) [4], [5], [6].

3GPP is an engineering organization that develops technical specifications. These technical specifications are then transposed into standards by the seven regional Organizational Partners that form the 3GPP partnership. The project covers cellular telecommunications technologies, including radio access, core network, and service capabilities [6].

Table 1-1: 3GPP Organizational Partners

Organization	Country / Region
Association of Radio Industries and Businesses (ARIB)[6]	Japan
Alliance for Telecommunications Industry Solutions (ATIS)[7]	USA
China Communications Standards Association (CCSA)[8]	China
European Telecommunications Standards Institute (ETSI)[9]	Europe

[6] http://www.arib.or.jp/english/
[7] http://www.atis.org/
[8] http://www.ccsa.org.cn/
[9] http://www.etsi.org/

Organization	Country / Region
Telecommunications Standards Development Society (TSDSI)[10]	India
Telecommunications Technology Association (TTA)[11]	South Korea
Telecommunication Technology Committee (TTC)[12]	Japan

The original scope of 3GPP was to produce technical specifications for a 3G mobile system based on GSM core networks. The scope has subsequently been extended to include the maintenance and development of technical specifications for evolved 3GPP technologies beyond 3G [6]:

- GSM and related 2G and 2.5G standards, including General Packet Radio Services and Enhanced Data Rates for GSM Evolution (EDGE)
- Universal Mobile Telecommunications System and related 3G standards, including High Speed Packet Access (HSPA) and HSPA+
- Long-Term Evolution (LTE) and related 4G standards, including LTE Advanced and LTE Advanced Pro
- 5G and related standards, including 5G-Advanced

Table 1-2: 3GPP Release Summary

Release	Timeframe	Summary
Release ’96– Release 7	1997–2007	3G specifications including IP-core, IP Multimedia Subsystem, push-to-talk, and technologies up to and including HSPA+ and EDGE
Release 8– Release 14	2008–2017	4G and related specifications including LTE, Worldwide Interoperability for Microwave Access, Multiple-Input Multiple-Output (MIMO) antennas, small cell, and carrier aggregation
Release 15– Release 18 (current)	2018–present	5G and related architectures, New Radio–based access and capabilities, satellite access, and network slicing

In October 2021, a 3GPP spokesperson was quoted as saying, “the organization’s formal work schedule doesn’t stretch much beyond 2023” [7]. However, many in the telecom industry speculate 6G will be included in the 3GPP Release 21 in the 2027 timeframe [7], [8], as “advanced 5G” topics are already being researched within the 3GPP working groups [9].

[10] http://tsdsi.org/
[11] http://www.tta.or.kr/eng/index.jsp
[12] http://www.ttc.or.jp/e

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2 Overview of 6G

6G is the next generation of cellular services beyond the widely deployed 4G and the current developing and deploying 5G specifications [10]. 6G specifications are merely speculation of metrics and performance not yet formally defined. Educated estimations are extrapolated from current trends of subsequent updates to cellular generations. Table 2-1 compares expectations for 6G metrics and performance against that of 5G.

Table 2-1: 6G Capability Comparison [11]

Capability	6G	5G
Peak data rate	> 100 Gb/s	10 Gb/s
User experience data rate	> 10 Gb/s	1 Gb/s
Traffic density	> 100 $Tb/s/km^2$	10 $Tb/s/km^2$
Connection density	> 10 $million/km^2$	1 $million/km^2$
Delay	< 1 ms	ms level
Mobility	> 1,000 km/h	350 km/h
Spectrum efficiency	> 3x relative to 5G	3~5x relative to 4G
Energy efficiency	> 10x relative to 5G	1,000x relative to 4G
Coverage percent	> 99%	About 70%
Reliability	> 99.999%	About 99.9%
Positioning precision	Centimeter level	Meter level
Receiver sensitivity	< –130 dBm	~ –120 dBm

A tremendous amount of required technology must be developed to realize 6G capabilities. Likewise, investment is needed in equipment at existing cell sites, deployment of new cell sites to meet minimum connection density expectations, and backhaul networks to service the ever-growing bandwidth demands of connecting everything. This move toward next generation applications and unprecedented connectivity is taxing current infrastructures and requiring new solutions.

The International Telecommunication Union "Network 2030" vision defines focus areas for the next generation of fixed network development, including:

- **Time Engineered Communications Services** – quality of service ensuring ultra-low latency for time-critical applications
- **Communication Services with Complex Constraints** – providing for quality of experience metrics to accommodate "holographic media and full-sensory immersive experiences that will lead to new application opportunities in a range of market verticals" [12]

- **Coexistence of Heterogeneous Network Infrastructures** – proliferation of public and private transits, inclusion of space communications, the densification of distributed edge compute, and a strong reliance on “next-generation mobile technologies […] beyond 5G” [12]

The Network 2030 vision articulates “an increasing chasm between the desire to push communication technologies into all aspects of life, while being increasingly conscious of the price to be paid in terms of energy and cost” [12]. While next generation applications push for more network capabilities, technological, financial, and social pressures temper the drive. The next sections discuss these issues.

2.1 Drivers

Communications and internet access are linked to positive economic benefits. Increasing internet access through cellular technology has contributed significantly to global economic growth [13], [14]. By 2035, it is predicted that services enabled by 5G alone will add over one trillion U.S. dollars of global economic output [2], [3].

Over 70% of the world population will have connectivity by 2030, coinciding with a 33% increase in user mobile devices to an estimate of just over 13 billion. Machine-to-machine (M2M) connections are projected to grow at a 30% compound annual growth rate from 2018 to 2023, representing the largest increase in access modality [15]. Total connected devices will number well into the tens of billions by 2030 [15], [16]. The desire for ubiquitous internet access along with ever-increasing throughput and near-real-time response for innovative applications is pushing current mobile access networks toward performance goals that are difficult, if not impossible, to achieve with existing infrastructure.

Current 5G technology presents trade-offs on latency, energy, throughput, and end-to-end reliability. The requirements of typical mobile broadband access for users versus ultra-reliable low-latency communications often required for M2M are addressed by different 5G network configurations: “5G spectrum alone will not be able to support the increased demand for the already ultra-dense deployment of devices” [16]. 6G architectures will be developed to jointly meet stringent network demands while providing nearly ubiquitous access for typical mobile broadband usage [1].

2.1.1 Traffic Flows

Typical mobile broadband use is an example of “north/south” traffic; that is, traffic that flows between an endpoint and the core network, cloud, or centralized service. This may be optimized through content delivery networks that bring content closer to users, but there is still a backhaul transit component to this traffic. Emerging applications like Vehicle Ad-hoc Networks are examples of “east/west” edge traffic; that is, traffic that flows between edge nodes without the need to transit backhaul networks for core or cloud access. Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure are good examples of life-critical systems that rely on direct, dynamic edge node connections or access to robust edge compute based on the need for ultra-low latency and near-real-time response.

The typical north/south traffic flow for mobile networks is changing with the introduction of sensor networks, autonomous driving, and smart cities; more data is moving east/west. These data-centric applications will require unprecedented:

- connection density on the order of 10^7 connections per km^2,
- traffic density on the order of terabits per second, and
- ultra-low latency on the order of microseconds.

These expectations may exceed the capabilities of emerging 5G systems [1].

Table 2-2: Predicted Data Rates and Latency for Application Classes on 6G Networks [17]

Use Case	Data Rate	Latency
Holographic Communications	10 Mb/s to 4.3 Tb/s (for a human-size hologram)	< 1 ms
Robotics/Industrial Automation	N/A	< 1 ms
Autonomous Driving	1 Gb/s for V2V (aggregate)	< 1 ms
Healthcare/Telemedicine	1080p ~ 1–5 Mb/s 4K 360° ~ 15–25 Mb/s hologram ~ 0.5–2 Gb/s (via point cloud)	< 1 ms (haptic feedback)

2.1.2 Future Application Requirements

Each successive generation of mobile access has focused on extending the performance of the network toward higher bandwidth, lower latency, and better reliability. 6G will be designed to address additional requirements of existing and future applications, including “global coverage, spectral efficiency, lower carbon footprint, cost effectiveness, bullet proof security, and embedded network intelligence” [14].

At the 6G Symposium in Fall 2021, VMware articulated a vision for internet evolution to support future applications. VMware’s vision starts with a reimagined edge as a globally distributed grid that creates a fabric of heterogeneous compute and intelligence to enable context-aware, immersive, and distributed applications anywhere, on demand. The requirements for this edge compute grid are driven by modern applications that require fungible resources to be allocated at the right place and at the right time, especially for mobility [18].

Future applications moving toward high bandwidth, low latency, immersive experiences are components of the “metaverse”—a fully realized digital world that blends physical and virtual into an immersive extended reality experience. The metaverse “will not be possible if there are not drastic improvements in today’s cellular networks” [19]. These improvements can come through convergence, namely computing-communications convergence, telecoms convergence for ubiquitous coverage, and the digital/physical convergence specifically for immersive data-sharing applications [14].

2.1.2.1 Computing-Communications Convergence

The separation of control plane and data plane and abstraction of software and hardware is enabling many virtual network functions to be distributed across carrier infrastructure. Mobile network architectures—from 3GPP's 5G standards, Service-Based Architectures, and ETSI's Multi-Access Edge Computing framework—"will increasingly address the interaction between computing and network functions to align with the software defined network" [14]. As the industry evolves toward 6G, "artificial intelligence will become an essential component of the network architecture," enabling automated operations, service management and orchestration [14].

2.1.2.2 Telecommunications Convergence

Ubiquitous network access is the key to truly immersive mobile experiences. Non-Terrestrial Network systems including remote and low-orbit satellites and unmanned aerial systems must be considered an integral part of telecommunications convergence. This requires 6G specifications "to offer great architectural flexibility to accommodate heterogeneous spectrum capabilities beyond the current terrestrial systems of today" [14]. It also requires that 6G provide high capacity, up to 1 terabit per second per base station, ultra-low latency below 1 millisecond, and reliability for mission-critical services through dynamic network slicing.

2.1.2.3 Convergence of Digital and Physical Spaces

The convergence of digital and physical spaces will allow users to visualize, simulate, and even operate physical objects through a digital interface. This is the real power of the immersive experiences—not simply displaying avatars in a virtual reality meeting space, but rendering connected digital twins of physical objects and allowing real-time interaction. Simulating real-world components in a digital domain will lower mean time to repair by predicting maintenance needs and preemptively scheduling downtime before failures occur, thus reducing the high costs associated with *unplanned* outages. This digital/physical convergence can be delivered only through widespread deployment of sensor networks. The 6G telecommunications convergence discussed in the previous section will play a fundamental role in realizing physical asset digitization and the creation of digital twins [14].

2.2 Challenges

The expected technical specifications for the path to envisioned 6G technology is an order of magnitude performance increase over existing 5G metrics. This presents several challenges in both network design and deployment economics toward meeting 6G ubiquitous coverage required for immersive data sharing. The next wave of realistic, immersive multimedia innovation is going to include avatar communications and digital twins. These applications have much more demanding network requirements "in terms of workloads, time sensitivity, intelligence, and quality of service, which could potentially challenge the way they are carried by current generation networks, including 5G" [14].

2.2.1 Latency

Predictions for latency metrics for 6G radio access networks are estimated to less than 1 millisecond. Gains must be realized in the radio access networks as latency on backhaul networks to core and cloud are fixed with distance. Improvements can be realized with edge compute, M2M direct communications, and more capable end devices. Latency requirements are also specific to and driven by the application use case.

The latency and throughput requirements for remote rendering (on 5G and beyond) are not yet clearly defined. Throughput and latency for remote rendering are highly dependent on virtual reality headset properties such as refresh rate and display resolution. Remote rendering can be set up for any common off-the-shelf rendering engine (e.g., Unity, Unreal) and middleware (e.g., Nvidia CloudXR, HoloLight ISAR[13]). However, the chosen hardware may require substantially different throughput and latency requirements—60 Mbps and 20 Mbps downstream throughput, respectively, according to specifications. Rigorous testing is required to determine the effects on user experience and usability [20]. A minimum latency is also originating from capturing the user's inputs, transmitting those to the mobile edge or cloud computing infrastructure, rendering the frame, encoding the frame for transmission, transmitting the frame to the headset, and decoding the frame for presentation on the headset.

In immersive experiences, sustained low latency is critical to making the user feel like the experience is natural or realistic. Walid Saad, who leads the Network Science, Wireless, and Security Laboratory at Virginia Tech, has been studying how indicators like latency affect a user's subjective experience in a virtual setting. Saad's team first characterized the user experience within their testbed wireless architecture by looking at how network attributes like link quality, network load, and available wireless and computing resources affect users' quality of experience in immersive environments. They determined latency to be a key performance indicator in predicting user experience. Saad concluded, "6G capabilities will be critical for the more demanding, futuristic holographic applications of XR [extended reality], which require near-zero latency along with high rates and reliability. 5G alone will not cut it" [21].

2.2.2 Spectrum

The evolution from 3G to 4G and into 5G was characterized by increasing availably of higher wireless spectrum bands and improvements in antenna technology. The challenge with 5G use of millimeter wave spectrum bands is the low penetration of signal and increase in noise from interference from any obstacles, such as buildings and trees in urban areas. Terahertz frequencies—currently speculated as a 6G technology—will provide higher throughput speeds but will only exasperate the interference issue [8]. Increases in antenna density to overcome blockages is already a challenge for 5G due to deployment cost models and simply will not scale to 6G. There is not yet a deployment model for infrastructure at that scale that is cost effective for a provider without a level of guaranteed subsidies or usage contracts [13].

Advances in spectrum management is one approach to accommodate 6G ubiquitous coverage. Spectrum management in 6G will be complex, incorporating the variety of spectrum bands and

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[13] Interactive Streaming for Augmented Reality

management models. Spectrum sharing will play an increasing role in accommodating new 6G systems. The speed at which new spectrum is being made available—close to a 10-year process—is no longer sufficient with the rapid technology development of mobile communication networks and changing user needs. Drastic shifts in spectrum management practices will be required to free up spectrum and develop sharing strategies to support 6G deployments [22]. If the current trend of auctioning government-held spectrum for commercial use continues, it is also reasonable to expect that an increase in “sub-6” and millimeter wave allocations will be made available. In addition, dynamic spectrum access and cognitive radio could further increase the bandwidth available to 6G networks [23].

Innovations in antenna technology will also be required to meet 6G goals of throughput, simultaneous connections, and ubiquitous coverage. The challenge with 6G is more about cell coverage than using simultaneous channels and multipath. For example, NTT Docomo tested an antenna system capable of creating a high-frequency mobile communication cell when a small piece of plastic is placed on top of a dielectric waveguide. The simple, low-cost antenna system can be embedded in floors, walls, ceilings, and work surfaces and can help lower energy use by efficiently propagating signals to desired areas only [24].

2.2.3 Power

Higher frequencies incur greater free space propagation losses, so they generally require more power to drive the signal over a shortened coverage area [8]. Smaller coverage areas require more base stations and antennas for ubiquitous coverage, consuming more power. On the receiver side, smaller form-factor sensors, devices, and wearables need extremely efficient batteries to provide the enhanced onboard compute for 6G applications as well as power the 6G receiver at the appropriate frequencies. Efficient use of power in 6G deployments will be a challenge to meet in a policy and regulatory environment that prioritizes energy independence and is already struggling to move from fossil fuels toward more sustainable renewable energy sources.

2.2.4 Economics

6G will required more infrastructure—not just upgrades to existing infrastructure, but additional equipment, towers, antennas, leasing costs, edge services, and other components to increase coverage density required for 6G ubiquitous access. Network infrastructure has very high fixed costs of delivery, so unless new business models can be realized, 6G deployment may be greatly affected by economies of scale and population density [25].

A 2017 Deloitte study for 5G deployment estimated “the United States requires between $130 and $150 billion over the next 5–7 years to adequately support broadband competition, rural coverage and wireless densification” [26]. Most of those costs are from fiber backhaul networks to support increased speeds for the growing number of connected devices. The report stated, “unless the United States significantly increases its deep fiber investments” 5G deployments could fall “far short of potential” [26]. This backhaul fiber shortage is only exasperated with 6G infrastructure deployment requirements.

Another issue is site densification; that is, installation and activation of new access points, towers, and antennas required for 6G ubiquitous coverage. Current 5G deployments are not meeting coverage requirements. A 2021 CostQuest study estimated an additional $36 billion is required to "ensure access to ubiquitous 5G for all Americans … not just those who will be covered by currently planned private investment" [27]. There is a growing concern around the economics of site densification. Adding new sites is a key requirement to increase wireless capacity, "but the current deployment model is prohibitively expensive" [13]. Site densification will also be exasperated with 6G infrastructure deployment requirements.

Efforts such as Open Radio Access Network[14] and Software-Defined Networks (SDN) with Network Functions Virtualization are evolving edge-to-core connectivity in 5G networks, and optimistic predictions of cost reductions are in the range of 64% operational expenditures and 68% capital expenditures [13]. This software-based approach can provide economies of scale to squeeze more performance from hardware. However, it applies only where hardware is centralized and can be consolidated—generally dense urban environments. The cost for ubiquitous coverage exponentially increases when including underserved, remote, rural areas where edge hardware still needs to be deployed before any virtualization can help. "There is a high probability that market-based ultrafast broadband infrastructure will mainly be the prerogative of urban and suburban areas" [13].

2.3 U.S. Leadership

Given the myriad challenges to realizing the advanced applications 6G will make possible, research and development must be prioritized to ensure recognized leadership in standards development and to benefit from the first mover strategic advantage.

As discussed in section 2.1.2 Future Application Requirements, sensor networks will play a fundamental role in the digitization of physical assets and the use of digital twin technology. China Unicom and Huawei are developing "smart super sensing networks" where "new sensing capabilities are introduced into traditional cellular networks to enable the creation of digital twins of various network infrastructure assets" [14]. The two companies are working with ecosystem partners and are developing an application platform around the concept. They are also "working with 3GPP and the China Communications Standards Association to bring this concept to 5G Advanced specifications" [14].

The slow U.S. approach to 5G may suggest difficulty in keeping pace with China and a lack of resolve in 6G research and development [28].

2.3.1 Equipment Bans

The United States began limiting Huawei network equipment from use in U.S. networks as far back as 2012. By May 2019, an executive order[15] effectively banned all Huawei equipment in the United States. The United States appealed to allies and other countries to join in prohibiting Huawei equipment in communications networks, including future 5G deployments. As a result, several other countries have issued bans of Huawei, including Australia, Japan, the United Kingdom [29], and, most recently, Canada [30], [31]. However, this defensive position is

[14] https://www.o-ran.org/
[15] https://www.federalregister.gov/executive-order/13873

unfavorable and may become untenable as demand for next generation mobile infrastructure increases and the United States does not have a company that is competitive in the full stack of 5G equipment [29]. By contrast, both Huawei and ZTE are among the top 5 leaders and visionaries, according to Gartner's 2022 ranking of 5G network infrastructure companies [32].

2.3.2 Rip and Replace

Another challenge for maintaining exclusion is the difficulty in unseating an incumbent. "Once Huawei builds a country's 5G network, that country is likely to choose Huawei to upgrade those systems when newer technologies become available" [33]. Huawei has already finalized several 5G contracts for networks in Europe [29]. In Africa, over 70% of the continent's 4G networks use Huawei technology [33].

The U.S. government set aside about $5.6 billion for the Secure and Trusted Communications Networks Reimbursement Program to "cover the costs of removing, replacing, and disposing of insecure equipment and services in U.S. networks produced or provided by Huawei Technologies Company and ZTE Corporation" [34]. In February 2022, Federal Communications Commission (FCC) chairwoman Jessica Rosenworcel notified Congress that the FCC had received 181 applications from carriers and providers for reimbursement [34].

2.3.3 Looking Ahead

"In the longer term, the United States must be better prepared for the arrival of 6G" [29]. The United States needs to fund 6G technology research and development at universities and create policies and incentives to encourage private sector investment in 6G. A target for success should be "at least one competitive U.S. company" in the 6G space [29].

In May 2021, the U.S. Senate passed legislation[16] "intended to boost the country's ability to compete with Chinese technology, including $54 billion for semiconductor and telecommunications equipment research" [35]. In December 2021, the U.S. House of Representatives passed Future Uses of Technology Upholding Reliable and Enhanced (FUTURE) Networks Act[17]" requiring the FCC to "establish a 6G Task Force and investigate how to design and deploy 6G technologies in the country" [36]. Both bills still require passing the other chamber of Congress and being signed into law. The FUTURE Networks Act's proposed task force will comprise representatives of communications industry companies, public interest organizations, and academic institutions. It will "assess the status of the industry-led standards-setting bodies currently working on 6G standards and share possible 6G use cases and any shortcomings of such technology, including any supply chain or cybersecurity limitations" [36]. The task force would have up to one year to finish the study. While good intentioned, an additional year from an uncertain congressional approval date sometime in the future mirrors the perceived slow U.S. approach to 5G rather than better preparing for the arrival of 6G.

[16] https://www.congress.gov/bill/117th-congress/senate-bill/1260/text
[17] https://www.congress.gov/bill/117th-congress/house-bill/4045/text/

2.4 Possibilities

This section described the expected 6G capabilities, the application drivers pushing networks to increase performance and coverage, and the technical, financial, and social challenges associated with realizing the vision. The next section makes some assumptions about meeting the challenges and discusses the possibilities of design, performance, and immersive data use cases that ubiquitous 6G networks could create.

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3 Immersive Data Sharing

"The next wave of multimedia innovation is going to be more realistic, immersing the real world with the virtual world of things to enable a new type of application, including avatar communications, digital twins of things, and sensor networks" [14]. Immersive data sharing goes beyond the capabilities of immersive data visualization—the latter primarily for interacting with and understanding large data sets. Immersive data sharing is about creating experiences in a way that two-dimensional (2D) or even three-dimensional (3D) charts, graphs, and visuals simply cannot convey. Immersive data sharing includes the human-to-information interface, but also extends to M2M interfaces as well as ubiquitous network access, which further enhances the ability to generate innovative applications and experiences.

This paper focuses on augmented reality and virtual reality (AR/VR) as they are likely the most data-demanding use cases for new applications on future 6G networks. The sheer torrent of data for *volumetric video* applications coupled with the expected density requirements for end points will require innovative network approaches beyond what 5G alone can provide.

3.1 Overview

Data visualization in its most common form is the 2D charts and graphs used to convey information. "Immersion—when applied properly—allows users of all technical skill levels to ingest huge amounts of complex data without increasing their cognitive load" [37]. The combination of immersive data visualization strives to create VR and AR experiences that are "the most effective mediums for visualizing, analyzing, and communicating insights from big data" [37]. From the foundational paper "Immersive Analytics," experiences built on technologies such as large touch surfaces and immersive virtual and augmented reality headsets will help in the detailed analysis of complex, big data sets [38].

Immersive data sharing is more than just analyzing big data. Immersive data sharing in 6G is about building interactions for collective participants in a combined experience that dramatically increases the efficacy of the encounter's purpose while maintaining loose requirements on physical assets and proximity.

Today's immersive experiences are confined to a few users in a single room connected to a server. In the future, 6G systems will enable extended reality services to operate "more seamlessly, long-distance, and in big spaces like stadiums, concert venues, and theme parks" [21]. However, to realize these very precise interactions between the physical and virtual worlds with "context-aware, immersive and distributed applications" [18], "we need higher data rates, increased reliability, and very low latency" in the cellular networks [21].

3.2 Data Demands of Immersive Applications

With immersive communications defined, the answer to the question *"what kind of future network can support immersive communications"* can be synthesized. The first step in addressing that question is to quantify exactly what kind of network performance these applications demand in terms of latency and throughput. In this paper, we consider the most data-intensive use case of immersive applications—extended reality (XR). More specifically, we consider the visual components of XR. If the benchmarks of XR can be met, the other, less demanding use cases will be within the capabilities of the network.

Extended reality is a blanket term that covers many modes of virtual and augmented reality in which real-world inputs are mixed with virtual assets to create an immersive experience. This can be achieved by projecting AR video onto a translucent display, superimposing video recorded by a VR headset onto the VR video, and potentially mixing other inputs and outputs, such as haptic or olfactory, into the experience. Again, however, this analysis focuses on the transmission of video.

3.2.1 Media Metrics for Immersive Video

Media can be streamed through an AR/XR headset in several different formats that are best broken down into three categories: stereoscopic video, spherical video, and volumetric video. The following subsections detail the formats in increasing order of data demand, based on the user's degrees of freedom to explore the video they receive on the headset. Below, we present typical modern metrics for quality VR/AR, against the maximum human perceivable metrics according to:

- Framerate: 90 Hz at least, potentially120 Hz
- Resolution: about 1.2 k2 pixels per eye
- Motion-to-photon latency18: about 5 ms, but compensated through asynchronous reprojection,19 could be up to 300 ms

3.2.1.1 Stereoscopic Video

A VR or AR headset consists of two square screens directly in front of each eye. The screens typically contain the same image with two slightly different perspectives to create the illusion of three-dimensional depth. The bare minimum media that must be transmitted to the headset to present an image to the user is video that fills both screens. A typical headset has two 2,000x2,000 pixel screens, one for each eye. The data demands are about the same as transmitting 4k resolution video.

This is considered zero degrees of freedom (0DoF), as the user receives only exactly the frames that will be viewed on the headset in 2D video. Higher degrees of freedom could conceivably be emulated in this setup if the motion of the user were to be transmitted across the network to fetch the correct frames for their orientation. However, this would introduce more latency into the system and would require an extremely low latency network to still meet the motion-to-photon latency requirement for immersive AR or VR.

Data rate = pixels x color depth x frames per second

[18] "The time from when the user moves their head or moves an input device, to the time when that change appears on the display is referred to as motion-to-photon latency. In order for most users to be comfortable and for VR to feel immersive, the motion-to-photon latency needs to be under 300ms" [42].
[19] Asynchronous reprojection is a graphics technology that ensures high performance by adjusting the position of the rendered frame just before it is seen by the user, to account for rotational user head movement [67].

3.2.1.2 Spherical Video

A more immersive format to transmit VR or AR video is spherical video. This is a projection of a spherical video frame onto a rectangular image, which is transmitted all at once so the user can pan their field of view (FOV) across the sphere in real time. However, for a stereoscopic effect, one sphere must be sent to each eye, and only about 90x90 degrees can be viewed at once. This means that for the perceived resolution rendered on the headset, eight times the resolution of spherical video (one quarter of the horizontal FOV and one half of the vertical FOV) must be transmitted.

The data rate is calculated the same way as for two-dimensional video, but there are considerably more pixels to transmit because only part of the image is inside the user's FOV.

3.2.1.3 Volumetric Video

Volumetric video is a drastically different format of video in which three-dimensional assets are transmitted directly, not rendered in frames. All six degrees of freedom (6DoF) are explorable by the user at any time, or by multiple users simultaneously. Frames do not consist of pixels, but rather mesh-based (consisting of polygons) or point-based (consisting of voxels) data, so that every face of every entity in the video can be viewed from any angle at any time.

Although more data intensive and less compatible with current hardware, point-based volumetric video is more practical than mesh-based video for live transmission of 3D objects across a network. This is because the data can be sent as it is recorded by LIDAR (Light Detection and Ranging) or other 3D videography systems—there is no need to project onto mesh surfaces or perform postproduction cleanup. Lastly, this format incurs additional overhead because the 3D objects must ultimately be viewed by humans in two dimensions (perhaps excluding a true holographic display that does not track individual viewing angle). A user's headset would have to complete the final rendering onboard, consuming power and computation resources.

The data rate for point-based volumetric video is governed by the number of voxels in the image; each has a color depth and typically four bytes of coordinate information per axis.

Data rate = 4 bytes per coordinate x color depth x number of points

3.2.2 Compression Rates

Video transmission is typically compressed because video tends to contain sequences of frames that are very similar to each other, so compression algorithms can save extremely large amounts of bandwidth by leveraging this property. To arrive at a reasonable data rate for each of the previously discussed video formats, this paper assumes one compression ratio across all formats. Still, it is worth mentioning and keeping in mind that video compression rates for all algorithms will vary based on the content being transmitted, so the assumed rate will be an approximation of the average compression ratio.

Based on literature associated with the H.264/AV2 compression algorithm [39], [40], typical video compression ratios fall within 1:30–1:60. This paper uses 1:50 because it is within the range, and not too conservative or aggressive.

In addition, volumetric video may not be compressible to the same degree as two-dimensional video. This paper assumes volumetric video compresses the same as two-dimensional video because it should have some of the same properties that make two-dimensional video compressible (e.g., small difference in the data sent for each frame), and there are not well-established algorithms to present as an alternative [41].

3.2.3 Data Rate Computation

For each of the use cases, data rates are estimated by the following equation:

$$Data\ Rate = N_{pixels} \times Bit\ Depth \times 3 \times Frame\ Rate \times Compression\ Ratio$$

Table 3-1: Volumetric Video Requirements

	N_{pix}	Bit Depth	FPS	Comp. Ratio	Data Rate
0DoF 4k	3,840 x 2,160	8	90 Hz	1:50	358 Mbps
3DoF Spherical	4,096 x 4,096	8	90 Hz	1:50	725 Mbps
6DoF Volumetric	~4,000,000	24+32+8	90 Hz	1:50	1.04 Gbps

Table 3-1 above summarizes the drivers for overall data rate outlined in this section and uses them to approximate a characteristic data rate for each immersive video format to be used in the coming sections to calculate the capacity of future networks to handle this type of traffic.

3.2.4 Latency

Finally, we address latency requirements for an AR or VR experience and the inherent concerns that impact the system. The latency requirement for a VR or AR experience is governed by human perception. The time from when the user moves an input device to that change being reflected on the display is referred to as the motion-to-photon latency [42]. Humans are very perceptive of this type of latency. Twenty milliseconds of motion-to-photon latency is about the limit to what can be tolerated without much perception of lag. However, in three degrees of freedom (3DoF) transmission, latency can be compensated for via asynchronous reprojection [43].

In addition to network latency, the system experiences computation latency due to the decoding and decompression of the video on the headset. The more the video is compressed, the more computation resources are required on the user end to decompress and display the video, creating a trade-off between network load and delay or power consumption depending on the compression algorithm used. In addition, 6DoF volumetric video has even more decoding cost on top of compression to be rendered and displayed on the headset, introducing even more computation latency.

3.3 Capacity of Current and Future Networks to Support Immersive Communication

Declaring the data throughput capacity of a cell network is complicated and can depend on many factors and potential bottlenecks. The available bandwidth at the base station, the signal-to-noise ratio impacting modulation code rates, and the capacity of the core network all can impact how many users demanding a certain amount of data can be supported simultaneously. For this exploration, we are primarily looking to see if future radio access technology and new spectrum could bring demanding data rates that were impossible under modern networks into reality under future networks. In this case, the absolute upper bound will be governed by the total amount of spectrum available, the maximum modulation code rate the tower can handle, and the extent to which MIMO arrays can increase the overall spectral efficiency of the channel.

3.3.1 A Refresher on LTE/5G Frame Structure and OFDM Symbols

The upper bound for the total amount of data a cellular channel can transmit across the radio channel is governed by

1. The quantity of frequency by time resource elements available
2. The maximum number of useful bits that can be transmitted in each of these elements

The former is in technical terms the number of Physical Resource Blocks (PRBs) in the channel and their length in time, and the latter is the maximum Modulation and Coding Scheme (MCS) supported for each of those PRBs. The cell bandwidth determines the quantity of PRBs, and the maximum MCS is a property of the base station [44].

- 1 PRB = 12 subcarriers x 7 symbols
- 2 PRBs per subframe (2 slots, the smallest unit of scheduling)
- One resource element (1 subcarrier x 1 symbol) is a single Orthogonal Frequency Division Multiplexing (OFDM) symbol
- Bits per OFDM symbol depends on MCS

Table 3-2: OFDM Modulation Bits per Subcarrier

Modulation	Bits per Subcarrier
Binary Phase Shift Keying (BPSK)	1
Quadrature Phase Shift Keying (QPSK)	2
16 Quadrature Amplitude Modulation (QAM)	4
64 QAM	6
256 QAM	8

Based on these factors, a maximum possible throughput *T* for a given cell can be calculated as the following:

$$T = \frac{N_{PRB} N_{subcarriers} N_{symbols} B_{symbol}}{PRB\ duration}$$

However, there are factors that are not considered in this simplified equation. First, the binary data carried by the symbols will also be encoded with redundant bits to allow for some error correction, and the quantity of redundant data will be determined by the channel quality. The ratio of non-redundant bits to the total available bits is referred to as the code rate, shown below as R_{code}, which will be some number less than 1. Also, not all PRBs or symbols are dedicated to the shared channel; there are control channels on either end of the band consisting of one or more PRBs, reference symbols throughout the channel, and information blocks transmitted at fixed intervals. This additional overhead would reduce the available symbols by some amount, estimated around 15–20%.

$$T = \frac{N_{PRB} N_{subcarriers} N_{symbols} B_{symbol} R_{code}}{PRB\ duration} \times (1 - OVH)$$

In addition, there is further overhead on the channel depending on the duplex method configured on the cell. In frequency division duplexing (FDD) cells, there are separate uplink (UL) and downlink (DL) bands, so there is no additional overhead to the bandwidth given to each channel. However, in time division duplexing (TDD), the uplink and downlink share the same band, and their resources are divided in time. In this case, the total throughput for the uplink or downlink channel is simply the throughput of the entire band divided by the ratio of time resources dedicated to that channel. For example, if one were calculating the channel throughputs of a TDD cell with a 4:1 downlink to uplink ratio, they would take 80% of the total throughput for the downlink channel and 20% for the uplink.

$$T_{DL} = T \times Ratio_{DL:UL}$$

$$T_{UL} = \frac{T}{Ratio_{DL:UL}}$$

3.3.2 MIMO Streams

Another caveat to total cell throughput is the Multiple-Input Multiple-Output (MIMO) configuration of the cell. MIMO leverages an array of antennas on both the transmitter and receiver and ample scattering between them to transmit multiple streams of data simultaneously. For MIMO to be effective, a combination of the array configuration and channel scattering must create enough spatial diversity in the channel to separate the data streams when they are received. MIMO configurations are referred to by the number of transmit and receive antennas the pair has at their disposal. For example, 8x8 MIMO would refer to a transmit and receiver pair each with eight antennas. This configuration supports a maximum of eight separate data streams, but the cell may only explicitly support a number of streams less than or equal to that [45]. Each stream the channel successfully supports could match the throughput of the same bandwidth of the equivalent Single-Input Single-Output (SISO) configuration, so the total throughput of a MIMO cell is:

$$T_{MIMO} = T_{SISO} \times N_{Streams}$$

3.3.3 Traditional LTE Base Stations

A sample, common base station for a traditional current cell deployment would be a 20 MHz band at about 1.7 GHz. This deployment would be an FDD configuration, with 15 kHz subcarrier spacing, 100 PRBs in the channel, and a maximum modulation scheme of 64 QAM. If we assume a code rate of 1, maximum throughput is shown in Table 3-3.

Table 3-3: Traditional LTE Base Station Metrics

Property	Value
Bandwidth	20 MHz
Max. Modulation	64 QAM
PRBs	100
Subcarrier Spacing	15 kHz
Symbols per 1 ms	14
MIMO Streams	2
Overhead	0.18
DL:UL **Ratio**	N/A (FDD)
Max. Downlink Throughput	165 Mbps

3.3.4 FR1 5G Base Stations

More recently, 5G cells are being deployed in the upper bands of frequency range (FR) 1 (sub-6 GHz), utilizing wider bandwidths and TDD configurations. A sample 200 MHz cell operating in the 3 GHz range is shown in Table 3-4.

Table 3-4: 3.48–3.8 GHz Metrics

Property	Value
Bandwidth	100 MHz
Max. Modulation	256 QAM
PRBs	1,056

Property	Value
Subcarrier Spacing	60 kHz
Symbols per 1 ms	56
MIMO Streams	4
Overhead	0.18
DL:UL Ratio	4:1
Max. Downlink Throughput	567 Mbps

3.3.5 FR2 5G Millimeter Wave Base Stations

Continuing the trend of higher frequencies, wider bandwidths, and more ambitious MIMO schemes would be an FR2 5G cell utilizing a millimeter wave (mmWave) band. These cells can utilize significantly more bandwidth and potentially leverage a larger quantity of MIMO streams, but the propagation characteristics of the band severely limit the cell size. Metrics are shown in Table 3-5.

Table 3-5: 5 GHz and mmWave Metrics

Property	Value
Bandwidth	800 MHz
Max. Modulation	64 QAM
PRBs	528
Subcarrier Spacing	120 kHz
Symbols per 1 ms	112
MIMO Streams	4
Overhead	0.18
DL:UL Ratio	4:1
Max. Downlink Throughput	11.2 Gbps

3.3.6 6G High-Band Base Stations

6G promises to further the efforts started in 5G to acquire more spectrum and access wider swaths of contiguous bandwidth. It is anticipated that large amounts of high-band spectrum (24–300 GHz) will be made available for 6G in allocations of up to 10 GHz of contiguous spectrum [46]. These high-band networks may offer significant improvements over comparable 5G deployments due to more available bandwidth and improved MIMO technology. Table 3-6 estimates the available throughput through similar assumptions to 5G mmWave, as the technologies should be applicable to this spectrum as well, and account for future improvements of MIMO antennas and processing.

Table 3-6: 6G High-Band Metrics

Property	Value
Bandwidth	~10 GHz
Max. Modulation	128 QAM
PRBs	~2,000
Subcarrier Spacing	120 kHz
Symbols per 1 ms	112
MIMO Streams	4
Overhead	0.18
DL:UL Ratio	4:1
Max. Downlink Throughput	~50 Gbps

3.3.7 Terahertz Communications

Aside from general improvements to performance in low-, mid-, and high-band cells, projections for future 6G networks often propose terahertz links as a solution to extremely data-demanding applications. Continuing the trend of higher total bandwidth and more propagation challenges to an extreme degree, Terahertz spectrum is a unique option in both its colossal bandwidth availability and its propagation that requires guaranteed line of sight to sustain a reliable link. A channel bandwidth of 15 GHz or more is within reason for a THz cell, but all connections would likely require line of sight, and even a small indoor cell may require very sophisticated beamforming and handoff to realize a reliable, optimized network [47].

To estimate a hypothetical cell's total capacity, this paper extends the spectral efficiency of a 240 kHz subcarrier spacing 64 QAM 5G band through the entirety of the 15 GHz band. In reality, the mathematics would likely be different, but in the absence of a real THz channel to base the example on, this approximation will make do. Metrics are shown in Table 3-7.

Table 3-7: Terahertz Communications Metrics

Property	Value
Bandwidth	>15 GHz
Max. Modulation	128 QAM
PRBs	~2,500
Subcarrier Spacing	240 kHz

Property	Value
Symbols per 1ms	224
MIMO streams	3
Overhead	0.18
DL:UL Ratio	4:1
Max. Downlink Throughput	~125 Gbps

3.3.7.1 Potential for Backhaul

Capacity is the key performance metric for backhaul networks. Latency, while important, is more critical in edge access and limited due to distance in backhaul networks. Designing for capacity then becomes the critical factor to optimize backhaul networks.

The capacity for backhaul networks is growing an order of magnitude with each cellular generation, from 10 s of Mbps in 3G networks to 100 s of Mbps and even a few Gbps in LTE, and is "estimated to grow to 10s of Gbps in 5G applications" [48]. Upgrades for 5G deployments and future 6G deployments will include 10 GbE and 100 GbE interfaces as well as 400 GbE interfaces at distances up to a few hundred kilometers, with longer distances served by dense wavelength division multiplexing optics [49]. However, this requires substantial capital expenditures to upgrade equipment and, in some cases, trench new fiber to accommodate the capacity increase.

"The terahertz band (0.3 THz to 10 THz) is the next frontier in wireless communications for its ability to unlock significantly wider segments of unused bandwidth" [50]. However, terahertz communication suffers propagation losses from signal attenuation due to molecule absorption [50]. Still, "terahertz bands can be used as mobile backhaul for transferring large bandwidth signals between base stations" [50]. There are several advantages to using the terahertz band, including:

- Less disruptive – no need for digging or trenching for fiber
- Faster deployment – can quickly be installed and brought into service
- Flexible – easily redeployed when compared to fixed wired solutions
- Cost efficient – low installation and maintenance costs compared to fixed wired solutions

While E-Band (71 GHz–81 GHz) is enough to cover most current 5G solutions requiring up to 20 Gbps connectivity up to 5 kilometers, requirements change with new 6G service models. 6G immersive data builds on two new 5G service use cases: Internet of Things (IoT), via the massive machine-type communications, and mission-critical applications, via the ultra-reliable low-latency communications. Both require extremely different resources and SLAs from the network and are best realized through network slicing via SDN [51]. In 6G, dynamic network adaptation can provide resourcing for both service use cases simultaneously pushing over-the-air channel capacity needs way above 20 Gbps to as much as 100 Gbps [51]. As gigahertz services move from backhaul deployments, terahertz communications will fill the wireless backhaul void.

3.3.8 Concurrent User Capacity Limits for Each Deployment Type

Using the above assumptions about required data rate and cell characteristics, an approximate maximum for simultaneous users demanding these data rates supported by each configuration can be determined. Keep in mind, this is assuming the following very generous conditions:

- All users have favorable enough signal-to-noise ratio to use the maximum MCS for the cell.
- The scheduler can make perfect use of the cell resources.
- There is no packet error, or at least all errors are within what the MCS can correct.

With these assumptions, Table 3-8 shows the practicality of proposed use cases for 6G commercially and within the DoD.

Table 3-8: Concurrent User Capacity Limits

Radio Access Type	Total Throughput	Max Users Supported per Cell		
		0DoF (238 Mbps)	3DoF (483 Mbps)	6DoF (1.04 Gbps)
LTE AWS-3	165 Mbps	0	0	0
FR1 5G Midband	567 Mbps	2	1	0
FR2 5G (mmWave)	11.2 Gbps	47	23	11
6G High-Band	50 Gbps	200	100	50
Terahertz 6G	125 Gbps	500	250	125

3.4 Use Cases Within the DoD and Commercial Market

The purpose of presenting the capacity and data demands in the previous section is to better put into context future use cases for 6G for the commercial market and within the DoD. With this information we can estimate what network demand each use case would generate and create a hypothesis for what kind of network would be required to support it. Describing this network can help convey whether this use case is possible under 5G, will need to wait for a 6G network, or is so ambitious it may need to wait for a network even more sophisticated than what the industry projects for 6G. The factors estimated in these use cases are specifically:

- User density
- Individual user data demand
- Individual tower throughput required to satisfy demand
- Tower deployment density required to satisfy demand

Data demand will be estimated based on if the use case is VR/AR or non-VR/AR. If it is VR/AR, demand will be further classified by the degrees of freedom presented to the VR/AR user. This demand should fit into the LTE, 5G FR1, 5G FR2/mmWave, or 6G THz categories, or a combination of radio access types, to satisfy the throughput and density requirements. Ultimately for each use case, we look to answer, is this a 6G technology?

3.4.1 Immersive Mixed-Reality Experience

In this paper, we define an immersive mixed-reality experience as a suite of software-facilitated experiences in which users interact in a shared physical space augmented by shared virtual elements. This may also include users not in the augmented physical space who could interact with the virtual space in VR and be rendered to other users in AR. The technologies through which the environment is augmented could include visuals (AR), spatial audio, haptics, olfactory, or others. The combination of all these artificial sensory technologies is usually referred to as XR, or extended reality. Users can interact with each other and the digital environment in real time with minimal delay to render the changes and to propagate their interactions to the mixed-reality engine.

3.4.1.1 Technology Description and Data Demands

The primary technology driver for this use case is AR and VR visual rendering devices, as sight is the most detailed sense and demands the most data over a network. In this scenario, with users experiencing a large digital environment, it may not be possible to present them with the full 6DoF version of the environment to be rendered on their headsets. Instead, it is more practical to render the overlay in 3DoF for each user with edge computation at the cell, send the spherical video, and correct for latency with asynchronous reprojection.

Existing products in the marketplace for AR experiences include Microsoft HoloLens,[20] Magic Leap,[21] and Campfire.[22] Within the DoD, Integrated Visual Augmentation System (IVAS) is the primary effort to bring this technology to soldiers in a ruggedized package. However, none of these technologies are ready to deliver a truly immersive AR experience due to field-of-view limitations and the inability to render opaque objects. Waiting for a capable device could be the driving factor in delaying a system like this to a 6G network timeframe, however we will focus on the readiness of the network for this use case assuming a capable headset exists going forward.

Other technologies that contribute to an immersive XR experience include spatial audio, haptic input and feedback, and olfactory technology, but the visual component is likely to remain the primary driver of total data demand [52].

From our previous definitions, we would select 5G FR1 mmWave from our cell configurations, and 3DoF for our AR experience data rate. Twenty-three users per cell is a reasonable upper bound for an experience on a small scale, potentially in an urban or indoor environment. However, in a large outdoor environment, it is unlikely mmWave would be able to cover a wide enough radius per tower to serve the data given the poor propagation loss. While 5G network technologies may be able to deliver the peak data rate required, a truly immersive experience

[20] https://www.microsoft.com/en-us/hololens
[21] https://www.magicleap.com/en-us
[22] https://www.campfire3d.com/

would require a network more sophisticated than current mmWave cells to serve a large number of users.

3.4.1.2 DoD Use Case: STE-LTS

The most relevant use case for the DoD in immersive experience technology is the Army's initiative to develop a capability called the Synthetic Training Environment Live Training System (STE-LTS). STE-LTS is an immersive AR/VR experience being developed to support soldier training, which converges today's Live, Virtual, Constructive, and Gaming environments into one common synthetic environment. The STE will enable more realistic and complex training environments that reflect potential operations and future conflicts with adversaries equipped with weapon systems comparable to the U.S. military's capabilities [53], [54]. STE-LTS is currently prototyping solutions that incorporate the use of AR technology/systems that provide improved battlefield effects visualization and allow for interactions between live and synthetic entities, platforms, and weapons [55].

STE-LTS intends to support:

- Adjudication over a network of direct and indirect fire between trainees on site
- The same adjudication between live on-site trainees and remote trainees in VR
- Rendering of other units, terrain changes, and immersive environmental effects using AR

The scale of these simulations is initially intended to cover platoon-scale (20–50 soldiers) engagements, but the system designers aspire to support battalion-scale (400–1,200 soldiers) engagements over large outdoor areas. The needs of this use case differ from typical immersive AR experiences in that the quantity of concurrent users may be larger, and the service area is likely to be a domestic training area, which would be vast and contain foliage and other cover or mixed terrain. For this reason, mmWave or higher frequencies may be ill suited for this case, as they have poor penetration and soldiers seeking cover may fall out of range. Platoon-scale engagements may be able to utilize mmWave in small areas, but battalion-scale engagements may need to make do with FR1 bands to get ample coverage and utilize more rendering on the AR client or vehicle-based cells.

In addition to STE-LTS, the Army is developing a ruggedized AR headset specifically for combat and training use, called the IVAS. The uses for this system could include identifying targets, thermal overlay, or training experiences like STE-LTS. The headset is built on top of the Microsoft HoloLens technology and faces similar challenges to the other AR headsets in production [56]. The difficulty in designing an AR display that is truly immersive is also a contributing factor to the likelihood that a true immersive AR experience may not exist until 6G is available [57].

3.4.2 Digital Twin

A digital twin is a virtual model designed to accurately reflect the state of a physical object in real time. Sensors on the real object will convey critical performance data about the real object to the digital model, which allows the model to predict maintenance requirements, possibilities for performance improvements, and other insights that could be then acted upon on the real object [58]. This is different than a simulation, for two reasons: (1) the digital twin is a three-dimensional model derived from computer-aided design representations of the real object, not a system model in software; and (2) the digital twin ingests real-time data from sensors on the real object, and the data can be acted upon in real time, producing predictions in parallel to the real object's actions during operation [59].

From a technical perspective, a digital twin is a detailed 3D model of a system that exists in a remote computation site and is viewable from 6DoF by the end user in the field. This model likely has an exceeding large number of faces or points, but the model itself may only need to be transmitted once to the user, then performance information and updates about the model could be sent in real time to inform the rendering at the user end. To generate the data that updates the model, a sophisticated network of sensors is required to gather a variety of data about the usage and state of the object to be relayed to the model. Thus, a combination of IoT sensor networks, advanced analytics, and 3D technology to view and interact with the model are all required to implement a functional digital twin system [60]. Commercial use of this technology will be financially beneficial to companies: By leveraging predictive maintenance to repair parts before they fail, companies will avoid the significant costs associated with unexpected physical system failures, with industries like aviation leading the way due to their reliance on uniquely complex machinery [61].

Over the network, the system requires the ability to receive and display 6DoF 3D models but does not require frame-by-frame retransmission of the entire model. The model could be rendered on a 2D display, but there would be a benefit to using an AR or holographic display of the object if the display technology is available. The update latency is somewhat forgiving, likely up to one minute, as the viewable model does not need to be streamed live. There is a potential for high peak throughput when downloading the entire model, but the bulk of the network traffic would be frequent uplink connections with a high reliability requirement from the IoT sensor network to send sensor data to the analytics engine. As an aside, if holographic streaming is already supported on the device and network, then the entire application could be streamed to the holographic device and there would be little requirement for specialized applications or hardware on the user end. However, it is technically simpler to take the non-streaming approach.

The application, sensors, and 3D display technology do not exist in the current market. Current networks could probably run this application already if these technologies existed. This use case is largely limited by the availability of 6G user devices and applications, not the network infrastructure.

3.4.2.1 DoD Use Case: Field Maintenance for Aircraft and Vehicles

Due to the U.S. military's use of complex and unique vehicles and machinery, which require extensive training to maintain and operate, the availability of digital twin technology would be an immense aid to soldiers in the field. Savings in maintenance costs and safety improvements due to predictive maintenance and improvements to field repair speed and efficacy are among the most obvious benefits of this technology in a defense environment. The U.S. military is already exploring the technology to develop digital twin models for the T-71 Redhawk, F-16, and other vehicles and aircraft [62], [63], [64].

3.4.3 Holographic Communications

Holographic communications are the live transmission of three-dimensional video displayed on a specialized device, which allows viewing of the 3D media at multiple angles simultaneously. For most holographic communications use cases, the goal is to replicate the physical presence of a person (or other 3D being/object) via capture, transmission, and display technology such that it could replace a live physical presence with a digital one. The bar is very high for fidelity because sub-par renderings, framerates, or other inaccuracies can make the experience poor-quality or even unsettling. Because of this, even though the minimum viable transmission of 3D media does not necessarily require extreme data rates, the requirement for an effective holographic presence is very high, making the data requirements the most challenging of all the technologies discussed thus far. In addition, there is a lack of specialized hardware to decode volumetric video, so the computational overhead is far higher than that of 2D video of the same data rate [65].

Another constraint to holographic communications is the complexity of holographic displays, which are largely commercially unavailable. In the short term, this lack of availability alleviates the load on the network because it is unlikely multiple holographic communication sessions would be occurring within the same cell. However, there is another, larger constraint, which is volumetric video capture. Volumetric video is extremely tedious to capture and create, and current technology requires a very manual process to clean and post-produce volumetric video captured from dozens of cameras spread across arrays that can take up an entire room. Current technology is far from transmitting live volumetric video, and even further from offering a capture system that is commercially viable and not a bespoke setup[23] [66].

Based on the previous analysis in this paper, transmitting 6DoF live video requires at least 1 Gbps per user, if not more, depending on the number of points or polygons and the compression ratio. This means that a holographic communication system will require at least a mmWave-scale bandwidth, if not THz. The likelihood that holographic communications will occur indoors, with a low user density and without much mobility, also makes higher frequencies appealing as beamforming and MIMO are most effective in these scenarios.

3.4.3.1 DoD Use Case: Holographic Conferencing

The potential use cases for holographic communications within the DoD do not differ significantly from what is proposed for the consumer market. A 3D live presence may be beneficial to soldiers on long tours away from home, or for conveying rich information more effectively, but it is unlikely that these uses would be considered technology priorities over other use cases addressed in this paper. However, if the technology were to become affordable and practical via consumer products, it is likely the technology would be leveraged for defense use.

3.5 Analysis

Headset-based AR/VR is the 6G technology closest to a practical implementation, and early versions of immersive AR/VR may roll out on 5G networks. Large-scale experiences are likely

[23] https://www.microsoft.com/en-us/mixed-reality/capture-studios

going to need 6G networks. STE-LTS is in development and has been prototyped, but a scale implementation likely requires the advanced networking promised with 6G.

Digital twin is largely a cloud computation and modeling technology, and once the models are developed it could be supported by current networks. Once the application is developed, current technology can immediately put it to use in the field, but the utility is improved by increasing immersion with the data via AR/holographic display and vast amounts of streaming real-time sensor data.

Holographic communications are the most demanding network application as they require transmission of 6DoF video, which will absolutely require 6G network capabilities. However, with large 6G bandwidths, dedicated coding hardware, and displays, immersive 3D media can be streamed to thin, power-efficient clients with low latency.

While wireless networks are a limiting factor for these use cases, the current state of networks are more mature than the current state of extended reality displays and applications.

4 Conclusion

The use cases presented in this paper are intended to paint a picture for what immersive data sharing in 6G networks will look like. The insights are based on the intersection of innovative applications and specific DoD concepts of operation. The discussed applications will require unprecedented amounts of bandwidth, very low latency, and a large number of connected devices making full-featured, functional deployments the domain of future 6G networks. With 6G not yet defined, the time for taking leadership positions in key focus areas is now.

From a policy perspective:

- Engage in 3GPP to help define emerging specifications for 6G networks and technologies.
- Create legislation to incentivize domestic research and development in 6G technologies.
- Continue the ban on untrusted foreign equipment manufacturers, but this must be coincident with the emergence of trusted suppliers with equivalent or more advanced technology.

From a network perspective:

- Invest in or create subsidies for domestic backhaul infrastructure upgrades and expansion.
- Partner with service providers to develop new business models and incentives for rural markets where the economics of current demand-based, economies-of-scale deployments simply do not apply.

From a technology perspective:

- Unleash new spectrum in support of radio access and wireless backhaul to meet the projected demands of concurrent users and throughput requirements, a known problem with no easy solutions.
- Track and fund research and development in more sophisticated radio access technology operating above 6 GHz, power efficiency, mobile edge access, artificial intelligence and machine learning-based network adaptation, and other technologies required to realize 6G deployments.

There is also an ancillary opportunity for leadership based on the discussed applications 6G will enable. Current AR/VR headset technology, rendering software, video formats, compression, and capture and real-time streaming are amazing in what they can do today; however, there is a foreseeable gap between the current state-of-the-art and the future requirements to satisfy the immersive data-sharing applications enabled on 6G networks. Infrastructure is an expensive endeavor with thinning margins and an inability to directly compete with over-the-top, service-based business models. Infrastructure is required; however, there could be opportunity to capture market share and large returns with investment in the 6G equivalent of video streaming services.

Fully immersive VR displays will need to cope with more and more data per frame to make renderings more realistic. This means more efficient batteries to power advanced compute needed to decompress video transmissions, and power advanced antennas to increase available throughput. More compute is also required for more advanced sensors and algorithms to recognize and compensate for user movements in 6DoF, reducing motion-to-photon latency and creating the hyperreal immersive experience. AR headsets will also benefit from more compute to handle 3D depth layering of virtual and physical objects in the user's field of view. This again requires more efficient batteries, more efficient compute on the headset, and/or transmission of more data at near-real-time latency with advanced asynchronous reprojection algorithms to correct for motion. But technology advancements are needed well beyond the headsets—software engines, haptic wearables, real-time capture and render, and machine-to-machine communications for local scaling all present areas for research and development with large potential upside in both the consumer and DoD use cases of 6G immersive data-sharing applications.

5 References

[1] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan and M. Zorzi, "Toward 6G Networks: Use Cases and Technologies," *IEEE Communications Magazine*, vol. 58, no. 3, pp. 55-61, March 2020.

[2] IHS Markit, "The 5G Economy: How 5G Will Contribute to the Global Economy," IHS Markit, 2019.

[3] PwC, "The Global Economic Impact of 5G," PwC, 2021.

[4] W. Chai, "3GPP (3rd Generation Partnership Project)," TechTarget, [Online]. Available: https://www.techtarget.com/searchnetworking/definition/3rd-Generation-Partnership-Project-3GPP. [Accessed 15 February 2022].

[5] L. Casaccia, "Understanding 3GPP – starting with the basics," Qualcomm, 2 August 2017. [Online]. Available: https://www.qualcomm.com/news/onq/2017/08/02/understanding-3gpp-starting-basics. [Accessed 15 February 2022].

[6] 3GPP, "About 3GPP Home," 3GPP, 2022. [Online]. Available: https://www.3gpp.org/about-3gpp/about-3gpp. [Accessed 1 February 2022].

[7] M. Dano, "Ericsson suggests '6G Basic' standards could be released in 2027," Light Reading, 13 October 2021. [Online]. Available: https://www.lightreading.com/6g/ericsson-suggests-6g-basic-standards-could-be-released-in-2027/d/d-id/772773. [Accessed 1 February 2022].

[8] L. Clark, "Beyond 5G – Network 2030," Mpirical, 31 January 2020. [Online]. Available: https://www.mpirical.com/blog/beyond-5g-network-2030. [Accessed 10 March 2022].

[9] 3GPP, "Advanced plans for 5G," 3GPP, 6 July 2021. [Online]. Available: https://www.3gpp.org/news-events/2210-advanced_5g. [Accessed 13 June 2022].

[10] Ericsson, "Ericsson Mobility Report," Ericsson, Stockholm, Sweden, 2021.

[11] S. Chen, Y.-C. Liang, S. Sun, S. Kang, W. Cheng and M. Peng, "Vision, Requirements, and Technology Trend of 6G: How to Tackle the Challenges of System Coverage, Capacity, User Data-Rate and Movement Speed," *IEEE Wireless Communications,* vol. 10.1109/MWC.001.1900333, pp. 1-11, 2020.

[12] R. Li, M. Toy, D. Trossen, D. Humphreys, V. SARIAN, S. Bhandari, M. Essa, D. (. H. S. (Sim), A. Clemm, P. N. Wang, P. F. DeTurk, Y. Zhang, Y. Miyake, A. Borodin and K. Makhijani, "Network 2030: A Blueprint of Technology, Applications and Market Drivers Towards the Year 2030 and Beyond," ITU, May 2019.

[13] E. J. Oughton and Z. Frias, "The cost, coverage and rollout implications of 5G infrastructure in Britain," *Telecommunications Policy*, vol. 42, no. 8, pp. 636-652, September 2018.

[14] M. Saadi, "6G: The Network of Technology Convergence," ABI Research, New York, February 2022.

[15] Cisco, "Cisco Annual Internet Report (2018 - 2023)," Cisco, 2020.

[16] R. Singh and D. Sicker, "Reliable THz Communications for Outdoor based Applications-Use Cases and Methods," in *IEEE 17th Annual Consumer Communications & Networking Conference (CCNC)*, Las Vegas, NV, 2020.

[17] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland and F. Tufvesson, "6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities," *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1166-1199, July 2021.

[18] B. Pelletier, Interviewee, *The Future of Cloud & Edge - 6G Symposium.* [Interview]. 26 September 2021.

[19] S. Shead, "Meta says its metaverse ambitions won't be possible without better cellular networks," CNBC, 2 March 2022. [Online]. Available: https://www.cnbc.com/2022/03/02/meta-says-todays-cellular-networks-arent-ready-for-the-metaverse.html. [Accessed 3 March 2022].

[20] D. S. Panic, Interviewee, *Lead Cognitive Scientist, MITRE.* [Interview]. 2 February 2022.

[21] S. Irby, "Tapping into 5G and 6G cellular networks and artificial intelligence could make immersive technologies go further, faster," Virginia Polytechnic Institute and State University, 4 October 2021. [Online]. Available: https://vtx.vt.edu/articles/2021/09/eng-extended-reality-5G-6G-networks.html. [Accessed 15 December 2021].

[22] M. Matinmikko-Blue, S. Yrjölä and P. Ahokangas, "Spectrum Management in the 6G Era: The Role of Regulation and Spectrum Sharing," in *2nd 6G Wireless Summit (6G SUMMIT)*, 2020.

[23] S. Biswas, A. Bishnu, F. A. Khan and T. Ratnarajah, "In-Band Full-Duplex Dynamic Spectrum Sharing in Beyond 5G Networks," *IEEE Communications Magazine,* vol. 59, no. 7, pp. 54-60, July 2021.

[24] J. P. Tomás, "NTT Docomo unveils 'Drop-n-Prop' antenna," RCR WIreless News, 19 January 2022. [Online]. Available: https://www.rcrwireless.com/20220119/5g/ntt-docomo-unveils-drop-pop-antenna-6g. [Accessed 20 January 2022].

[25] R. L. Katz and T. A. Berry, Driving Demand for Broadband Networks and Services, New York: Springer Cham Heidelberg, 2014.

[26] D. Littmann, C. Wigginton, P. Wilson, B. Haan and J. Fritz, "Communications Infrastructure Upgrade: The Need for Deep Fiber," Deloitte, 2017.

[27] CostQuest Associates, "CostQuest National 5G Model: Methodology," CostQuest Associates, Cincinnati, OH, November 2021.

[28] N. T. Lee, "Navigating the U.S.-China 5G Competition," The Brookings Institution, April 2020.

[29] D. Sacks, "China's Huawei Is Winning the 5G Race. Here's What the United States Should Do To Respond," 29 March 2021. [Online]. Available: https://www.cfr.org/blog/china-huawei-5g.

[30] E. Hertzberg and B. Platt, "Canada Bans Huawei From 5G, Ending Years-Long Impasse," Bloomberg, 19 May 2022. [Online]. Available: https://www.bloomberg.com/news/articles/2022-05-19/trudeau-government-said-to-ban-huawei-from-5g-in-canada. [Accessed 20 May 2022].

[31] C. Tunney and R. Raycraft, "Canada bans Chinese tech giant Huawei from 5G network," CBC, 19 May 2022. [Online]. Available: https://www.cbc.ca/news/politics/huawei-5g-decision-1.6310839. [Accessed 20 May 2022].

[32] K. Takiishi, S. Fabre, F. Marsala, P. Liu, S. W. d. Grimaldo and P. Pandey, "Magic Quadrant for 5G Network Infrastructure for Communications Service Providers," Gartner, February 23, 2022.

[33] A. Mackinnon, "For Africa, Chinese-Built Internet Is Better Than No Internet at All," FP Group, 19 March 2019. [Online]. Available: https://foreignpolicy.com/2019/03/19/for-africa-chinese-built-internet-is-better-than-no-internet-at-all/. [Accessed 7 March 2022].

[34] Light Reading, "FCC's 'rip and replace' for ZTE and Huawei balloons to $5.6B," Light Reading, 4 February 2022. [Online]. Available: https://www.lightreading.com/security/fccs-rip-and-replace-for-zte-and-huawei-balloons-to-$56b/d/d-id/775112. [Accessed 7 February 2022].

[35] Z. Marzouk, "US Senate approves bill to counter China tech competition," ITPro, 9 June 2021. [Online]. Available: https://www.itpro.co.uk/business/policy-legislation/359814/us-senate-approves-bill-to-counter-china-tech-competition. [Accessed 20 January 2022].

[36] C. Castro, "US House of Representatives Passes 6G Task Force," 6G World, 2 December 2021. [Online]. Available: https://www.6gworld.com/exclusives/us-house-of-representatives-passes-6g-task-force/. [Accessed 9 December 2021].

[37] J. Tam, "What is Immersive Data Visualization Anyway?," Medium, 29 June 2020. [Online]. Available: https://medium.com/badvr/what-is-immersive-data-visualization-anyway-53f5216e87ab. [Accessed 13 December 2021].

[38] T. Chandler, M. Cordeil, T. Czauderna, T. Dwyer, J. Glowacki, C. Goncu, M. Klapperstueck, K. Klein, K. Marriott, F. Schreiber and E. Wilson, "Immersive Analytics," in *BDVA*, Hobart, Australia, 2015.

[39] K. Amerasinghe, "H.264 for the Rest of Us," Adobe, 2010.

[40] J. Golston, "Comparing Media Codecs for Video Content," Texas Instruments, San Francisco, 2004.

[41] L. Li, Z. Li, S. Liu and H. Li, "Rate Control for Video-Based Point Cloud Compression," *IEEE Transactions on Image Processing,* vol. 29, pp. 6237-6250, 2020.

[42] Google, "Fundamental Concepts," Google, 2019. [Online]. Available: https://developers.google.com/vr/discover/fundamentals. [Accessed 24 May 2022].

[43] D. Wagner, "Motion To Photon Latency In Mobile AR And VR," Medium, 1 August 2018. [Online]. Available: https://medium.com/@DAQRI/motion-to-photon-latency-in-mobile-ar-and-vr-99f82c480926. [Accessed 27 May 2022].

[44] Keysight Technologies, Inc., "LTE Physical Layer Overview," Keysight Technologies, Inc, 2022. [Online]. Available: https://rfmw.em.keysight.com/wireless/helpfiles/89600b/webhelp/subsystems/lte/content/lte_overview.htm. [Accessed 1 May 2022].

[45] R. Blum, J. Winters and N. Sollenberger, "On the capacity of cellular systems with MIMO," in *IEEE 54th Vehicular Technology Conference*, 2001.

[46] Samsung Electronics Co., Ltd., 6G Spectrum, Samsung Research, 2022.

[47] M. Polese, J. M. Jornet, T. Melodia and M. Zorzi, "Toward End-to-End, Full-Stack 6G Terahertz Networks," *IEEE Communications Magazine,* vol. 58, no. 11, pp. 48-54, November 2020.

[48] Ceragon, "5G Networks – Wireless and Fiber Backhaul Solutions," Ceragon.

[49] B. Lavallée, "Spotlight on 4G/5G backhaul networks," Ciena Corporation, 13 August 2020. [Online]. Available: https://www.ciena.com/insights/articles/spotlight-on-4g-5g-backhaul-networks.html. [Accessed 16 March 2022].

[50] National Instruments, "Wireless Industry's Newest Gambit: Terahertz Communication Bands," IEEE Spectrum, 17 April 2019. [Online]. Available: https://spectrum.ieee.org/wireless-industrys-newest-gambit-terahertz-communication-bands. [Accessed 14 March 2022].

[51] D. Cohen, "A Guide to Building Flexible Wireless Backhaul Networks," Ceragon, December 2020.

[52] Resonance Audio, "Fundamental Concepts," Resonance Audio, [Online]. Available: https://resonance-audio.github.io/resonance-audio/discover/concepts.html. [Accessed 23 May 2022].

[53] United States Army Acquisition Support Center (USAASC), "Synthetic Training Environment (STE)," United States Army Acquisition Support Center (USAASC), 2022. [Online]. Available: https://asc.army.mil/web/portfolio-item/synthetic-training-environment-ste/. [Accessed 1 May 2022].

[54] PEO STRI, "Synthetic Training Environment (STE)," U.S. Army, 2022. [Online]. Available: https://www.peostri.army.mil/synthetic-training-environment-ste/. [Accessed 1 May 2022].

[55] P. P. Malinovsky and A. R. Knight, "STE Live Network Assessment," The MITRE Corporation, Bedford, MA, October 2020.

[56] PEO Soldier, "Project Manager Integrated Visual Augmentation System PM IVAS," U.S. Army, 2019. [Online]. Available: https://www.peosoldier.army.mil/Program-Offices/Project-Manager-Integrated-Visual-Augmentation-System/. [Accessed 3 January 2022].

[57] C. M. Kenney, "Army Delays IVAS Display Headset by a Year," Defense One, 19 October 2021. [Online]. Available: https://www.defenseone.com/technology/2021/10/army-delays-ivas-display-headset-year/186217/. [Accessed 1 May 2022].

[58] W. Roper, "There is No Spoon: The New Digital Acquisition Reality," October 2020.

[59] W. G. Wong, "What's the Difference Between a Simulation and a Digital Twin?," Electronic Design, 24 May 2018. [Online]. Available: https://www.electronicdesign.com/technologies/embedded-revolution/article/21806550/whats-the-difference-between-a-simulation-and-a-digital-twin. [Accessed 29 November 2021].

[60] K. Shanmugam, "The Perfect Pair: Digital Twins and Predictive Maintenance," InfoQ, 10 March 2021. [Online]. Available: https://www.infoq.com/articles/digital-twin-predictive-maintenance/. [Accessed 29 November 2021].

[61] P. Daugherty, P. Banerjee, W. Negm and A. E. Alter, "Driving Unconventional Growth through the Industrial Internet of Things," Accenture, 2015.

[62] Boeing, "Boeing: T-7A Red Hawk," Boeing, [Online]. Available: https://www.boeing.com/defense/t-7a/index.page. [Accessed 3 January 2022].

[63] B. Brackens, "Air Force to develop F-16 ‘digital twin’," Air Force Life Cycle Management Center, 30 June 2021. [Online]. Available: https://www.aflcmc.af.mil/News/Article-Display/Article/2677215/air-force-to-develop-f-16-digital-twin/. [Accessed 3 January 2022].

[64] S. Waterman, "Air Force Goes All in on Digital Twinning - for Bombs As Well As Planes," Air Force Magazine, 26 March 2021. [Online]. Available: https://www.airforcemag.com/air-force-goes-all-in-on-digital-twinning-for-bombs-as-well-as-planes/. [Accessed 3 January 2022].

[65] F. Qian, B. H. J. Pair and V. Gopalakrishnan, "Toward Practical Volumetric Video Streaming On Commodity Smartphones," in *HotMobile ’19*, Santa Cruz, CA, 2019.

[66] O. Schreer, I. Feldmann, S. Renault, M. Zepp, M. Worchel, P. Eisert and P. Kauff, "Capture and 3D Video Processing of Volumetric Video," pp. 4310-4314, 2019.

[67] Google, "Asynchronous Reprojection," Google, November 2019. [Online]. Available: https://developers.google.com/vr/discover/async-reprojection. [Accessed 27 May 2022].

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Appendix A Abbreviations and Acronyms

0DoF	Zero Degrees of Freedom
1G / 3G / 4G / 5G	First/ Third / Fourth / Fifth Generation (cellular network)
2D	Two-Dimensional
3D	Three-Dimensional
3DoF	Three Degrees of Freedom
3GPP	Third Generation Partnership Project
6DoF	Six Degrees of Freedom
6G	Sixth Generation (cellular network)
AI	Artificial Intelligence
AR/VR	Augmented and Virtual Reality
BPSK	Binary Phase Shift Keying
DL	Downlink
DoD	Department of Defense
EDGE	Enhanced Data Rates for GSM Evolution
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FDD	Frequency Division Duplexing
FOV	Field of View
FR	Frequency Range
GSM	Global System for Mobile Communications
HSPA	High Speed Packet Access
IoT	Internet of Things
IP	Internet Protocol
IVAS	Integrated Visual Augmentation System
LTE	Long-Term Evolution
M2M	Machine-to-Machine
MCS	Modulation and Coding Scheme

MIMO	Multiple-Input Multiple-Output
mmWave	Millimeter Wave
OFDM	Orthogonal Frequency Division Multiplexing
PRB	Physical Resource Blocks
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SDN	Software-Defined Networks
SISO	Single Input Single Output
STE-LTS	Synthetic Training Environment Live Training System
TDD	Time Division Duplexing
UL	Uplink
V2V	Vehicle-to-Vehicle
XR	Extended Reality