MOBILE COMMUNICATIONS BEYOND 2020

THE EVOLUTION OF 5G TOWARDS THE NEXT G

A 5G AMERICAS WHITE PAPER

DEC 2020

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Executive Summary

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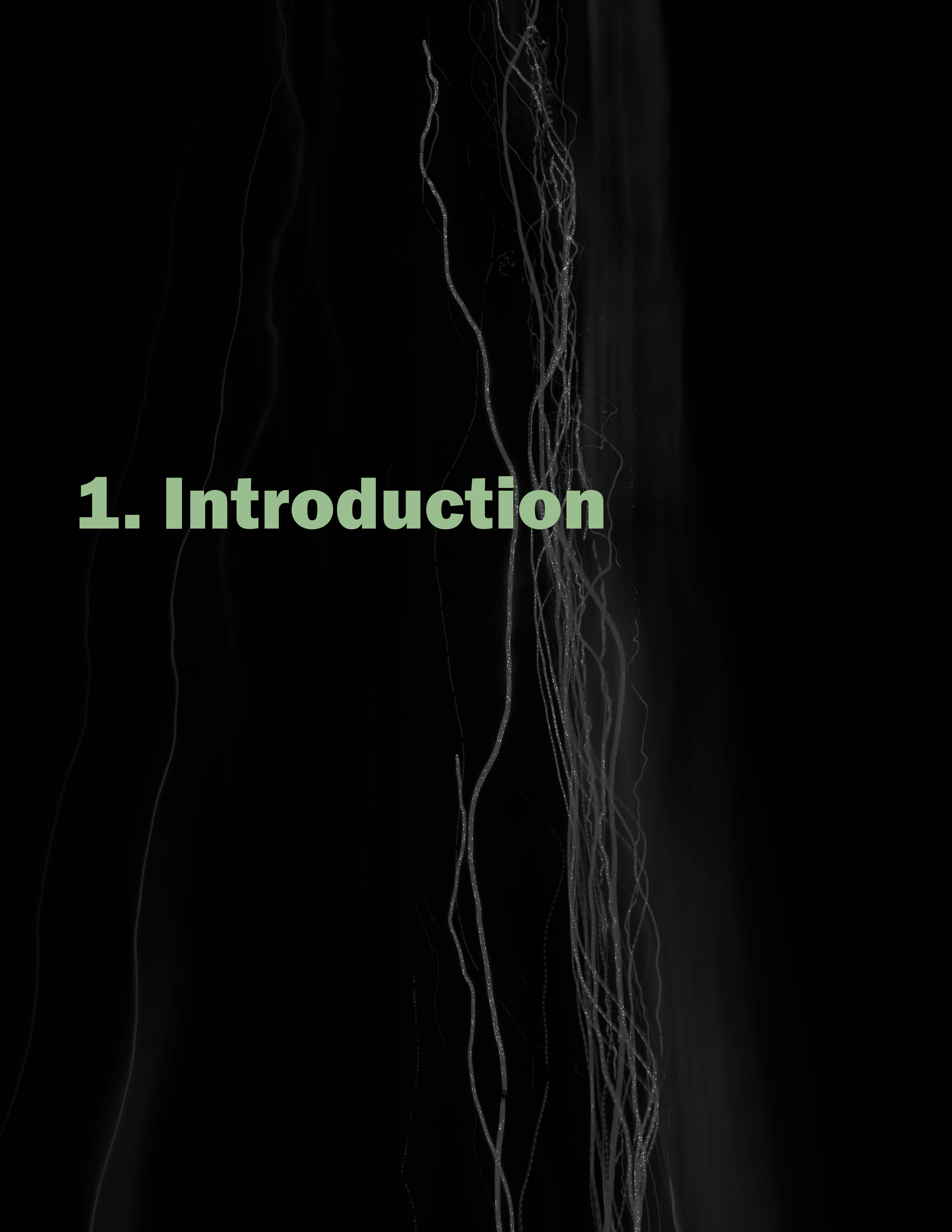
As the world is beginning to enjoy the benefits of 5G, the "fifth generation" of wireless cellular technology, the industry is starting to plan for the future set of requirements needed for its continued evolution, as well as for the next generation of mobile communications. Additional enhancements and evolution of the current IMT-2020 (5G) technology standards continue to be expected from the industry, just like it has been with all the previous "G's". For this reason, 5G Americas has reviewed "6G" concepts from Asia and Europe and is starting to review early 6G work in the United States. This white paper details this global work, comments upon it as appropriate, and presents some of the current use cases and technologies for consideration for the evolution of 5G towards the next G.

From a use case standpoint, 5G Americas has identified early specifications and requirements for autonomous driving and VR/AR ("virtual reality / augmented reality") uses. We expect to see continued growth and demand for these types of applications. Additional technologies such as edge computing, cloud services, and network virtualization are also already augmenting IMT-2020-based deployments and will continue to develop as new use cases and higher demands on the network are required. 5G and its evolution to the next G is a transformational technology working in concert with other enabling technologies to change the world of connectivity. Moreover, 5G Americas is also seeing the emergence of holographic communications, imaging and sensing, evolutions of massive IoT (mIoT), smart agriculture, and first responder services.

Due to the impact of these technologies, 5G Americas feels it is important to begin looking now, as an industry, towards the future to ensure the Americas' continued leadership in shaping the evolution of wireless technology. This paper evaluates technology trends and suggests how to enhance existing technologies towards the future evolution of wireless cellular networks beyond the current 5G.

It should be noted that while it is 5G Americas' mission to bring together advocates for LTE and 5G technologies across the Americas, including North, Central and South America, a large portion of this white paper will focus on specific needs for the North American market. In particular, we identify necessary goals for North American companies and organizations in expanding leadership activities to further the development of future wireless networks abroad. Our intent of this paper is to focus on the additional special requirements of North America.

1. Introduction



1 Introduction

This paper addresses three main topics:

- **A review of activities beyond 5G in both North America and globally**
- **How communications will change beyond the 2020s, including many use cases and emerging technologies that are being discussed. Note these use cases are the current discussions and may change as the industry evolves.**
- **How North America can establish and maintain technological leadership in future communications standards**

5G is still early in its lifecycle and is being evolved and enhanced through upcoming 3GPP releases while worldwide deployment continues. As of November 2020, there are 135 5G networks, which adhere to 3GPP standards. With unprecedented flexibility, it is expected that 5G will deliver many years of value to consumers and enterprises for the foreseeable future. As the industry builds upon the great work 3GPP has accomplished with defining New Radio (NR) and Service Based Architecture (SBA), it will simultaneously evolve these aspects and others of 5G in 3GPP Release 17 and beyond.

If history is any indicator, technology will likely continue to progress into another ITU-defined “IMT” into the 2030 timeframe. 5G Americas believes (as history has shown) this will probably be marketed as “6G” (and succeeding it will be a 7G, 8G, and so on each following a 10-year cycle). As of November 2020, there is no industry agreed definition or timeline for the successor to IMT-2020 or what will likely be called “IMT-2030” or 6G. However, output from the work on this next “IMT” vision and the goals that the ITU has identified is expected to show progress within the next few years, as there are already projects underway which impact technology evolution into the late 2020s and 2030s.

In addition, many projects identified as “Next G” and “6G” are already underway globally with some involvement from the Americas. This paper specifically discusses the current view of new and emerging use cases that will rely on developing technology that ought to be supported by government, commercial entities, and universities in the United States. These entities, through public-private partnerships, should actively engage today in scientific and applied research to maintain leadership in new technologies that will underpin 6G.

While 6G is expected to revolutionize radio, network technologies and architecture potentially based on new IMT requirements, it is not likely this work will appear in a 3GPP release until after Release 19 or 20, nor be ready for commercial deployment until around 2030.

This paper is focused on the evolution of 5G radio and network technology for capabilities not yet realized on the 5G network, and on the “Next G”/ 6G. Other 5G Americas white papers have previously focused on other significant areas of 5G development, including: 5G and the Cloud, 5G Services, Small Cells and 5G, 5G at the Edge, 5G Security and 3GPP Releases 16 and 17.

While users are just now coming to understand 5G, the work to develop 6G is already underway and North America needs to build and maintain leadership in this field. The final part of this paper is an overview at what this region can do to achieve this leadership.

2. Activities in North America

2 Activities in North America

In North America, Next G activities are primarily centered around academia with additional efforts from agencies of the United States government and SDOs (Standards Developing Organizations). Some of these academic bodies and standards organizations include the following:

- **ComSenTer** (Communications Sensing TeraHertz) is the initiative in the Joint University Microelectronics Program (JUMP), a sweeping five-year industry/academia partnership to accelerate innovation in microelectronics-based technologies, including wireless communications. Researchers at the University of California Berkeley, Santa Barbara, and San Diego are heavily involved in 6G research. ComSenTer is developing the technologies for a future cellular infrastructure using hubs with massive spatial multiplexing, providing 1-100Gb/s to the end user with 100-1000 simultaneous independently modulated beams, and with aggregate hubs capacities in the 10's of Tb/s. [1]
- **New York University (NYU) Wireless** is working on Terahertz, 6G & Beyond research. Their key areas of research include terahertz communications and sensing, mobile edge networking and computing, terahertz (THz) and quantum nanodevices and circuits, machine learning, communication foundations, and 6G testbeds. [2]
- **The mmWave Networking Group at the University of Padua** has its own 6G research group and they are also working closely with the NYU Wireless Group. [3]
- **The Institute for the Wireless Internet of Things (WIOT) at Northeastern University** is working on several active projects and research collaborations on 6G wireless systems.
- **Northeastern University Wireless Internet of Things (WIOT) and Interdigital** held a 6G Symposium in October 2020 [4]. Several high-profile speakers gave fireside chats on the evolution to 6G, including FCC Chairman Ajit Pai and Dr. Walter Copan of NIST.

Other universities working on 6G include the University of Texas at Austin, Georgia Institute of Technology, Arizona State University, University of Arizona, Virginia Polytechnic Institute, and Virginia Tech.

- **Wireless Networking & Communication Group (WNCG) of University of Texas at Austin** usually conducts a Texas Wireless Summit but 2020 Summit is postponed to Spring 2021. Their main research focus is application of radar for centimeter-precise telemetry, etc. [5]
- **Broadband Wireless Networking Lab of Georgia Institute of Technology is conducting research on terahertz-band communications and other 6G topics.**
- **Arizona State University** is focused on research areas like sensing, localization, large antenna arrays for devices, etc.

- **University of Arizona** is focusing on broadband wireless access and applications. The Broadband Wireless Access and Applications Center (BWAC) is a multi-university National Science Foundation (NSF) Industry/University Cooperative Research Center (IUCRC), led by the University of Arizona in partnership with University of Mississippi, Catholic University of America, and North Carolina State University. Along with NSF support, BWAC is funded by 20+ affiliate members from industry and Department of Defense (DoD) labs.
- **Wireless @ Virginia Tech** is working on technologies to cater 6G use cases like autonomous networks, connectivity in 3D space and aerial drones etc.
- **US National Science Foundation's Spectrum Innovation Initiative** began advocating for a new National Center for Wireless Spectrum Research (SII-Center) that would go beyond 5G. [6]

2.1 ATIS Call to Action

The Alliance for Telecommunications Industry Solutions (ATIS) has recently issued a call to action to promote U.S. 6G Leadership. [7] ATIS stated that the timeline for 6G development has already begun, as today's investments in 5G networks, devices and applications already point toward the future opportunities for 6G. Therefore, the journey to the next decade should begin now with deliberate, collaborative steps and an aligned commitment between government and industry to ensure the U.S. maintains a competitive technology position in 5G networks today and 6G networks in the future.

2.2 Next G Alliance

Recently, ATIS formed the "Next G Alliance" which is a bold new initiative to advance North American mobile technology leadership over the next decade through private sector-led efforts [8]. With a strong emphasis on technology commercialization, the work will encompass the full lifecycle of research and development, manufacturing, standardization, and market readiness. The Next G Alliance enjoys broad industry support with founding members coming not only from the ranks of most major telecom operators and suppliers, but also leading cloud/software and high technology companies.

The Next G Alliance will bring together diverse segments of the industry and leading research institutions. It is premised on the stance that applied research should be leveraged to ultimately create a pathway to product realization and commercialization. While innovation is still vital to this ecosystem, connecting the desired endpoint early in the research process to drive research priorities is central to development, standardization, manufacturing, and Next G readiness. While each of these areas could be incentivized and managed separately, aligning them to an overarching strategy and objectives allows each stage's outcomes to be managed across the entire lifecycle. The goal is to start with the end in mind of delivering results in terms of commercialization, ultimately to drive economic growth.

The goals of the Next G Alliance include providing North American 6G market leadership, spanning the full range from R&D, manufacturing, standardization, and market-readiness:

- **Advance North American global leadership over the 5G evolutionary path and 6G early development.**
- **Create a Next G development roadmap that will promote a vibrant marketplace for 6G introduction, adoption, and commercialization with North American innovation in mind.**
- **Develop a set of national priorities that will influence government applied research funding and promote incentivized government actions.**
- **Progress a North American model that promotes development across the full lifecycle of research to realization, aligned with commercialization outcomes.**

The Founding Members of the Next G Alliance held the inaugural meeting in November 2020. Founding Members will appoint a Steering Group and Working Groups will be created and launched in 2021. The eventual output of the Groups will include:

- **Next G National Agenda –** A 6G national roadmap that addresses the changing competitive landscape and positions North America as the global leader in the development, manufacturing, and adoption of Next G technologies.
- **Strategic Model for Success –** A means for aligning industry on a core set of technologies, research priorities and recommended government actions that will steer U.S. and North American regional leadership for 6G (and beyond) to influence government policies and funding.
- **Global Leadership –** Identifying and defining the early steps and strategies that will facilitate and lead to rapid commercialization of Next G technologies across new markets and business sectors and promote widescale adoption, both domestically and globally.

3. Review of Global Activities

3 Review of Global Activities

This section focuses on specific international efforts by leading nations in the wireless cellular industry outside of the Americas.

3.1 China 6G Efforts

On November 7, 2019, China officially launched research and development for its 6G mobile networks. (China starts development of 6G, having just turned on its 5G mobile network). The Ministry of Science and Technology set up two working groups. The first group consists of government agencies responsible for promoting 6G research and development. The second group, called as "China 6G Wireless Technology Task Force" consists of vendors, operators, China Research Agencies and China Universities. Their purpose is to form a panel tasked with laying out the development of 6G and proving its scientific feasibility. The Chinese Government has invested more than $30 billon towards 5G R&D over five years, and 6G may receive similar investments.

During the 6G Second Summit, China Mobile, Huawei and ZTE expressed the requirements, use-cases and technology enablers of 6G. According to ZTE, "3D-connectivity, intelligent MIMO, on-demand topology, on-demand AI, and new horizon communications, the light, the molecular, the brain cloud and the qubit will make up the five essential enablers of 6G networks." [9]

Other 6G research activities:

- **During 2019, Huawei kicked off research into 6G, including air interface technologies, new network architectures, and key enabling technologies**
- **During 2H 2019, China Unicom created a research group focused on terahertz communications, one of the core technologies for 6G**
- **ZTE disclosed its 6G partnership with China Unicom to explore three-dimensional connectivity, terahertz communication and the integration of communications and sensing technology**

3.2 Japan 6G Efforts

On November 20, 2019, Japan announced a stimulus pack of $2 billion to support industry research on 6G technologies (Japan readies $2bn to support industry research on 6G tech) with a timeline of 2020-2030.

On January 22, 2020, the Japanese government announced plans to develop a comprehensive 6G strategy. A 6G panel was created to discuss and analyze technology developments and use cases. The panel included private sector representatives and university researchers. (Japan announces plans to kick off '6G' research: Report)

In April 2020, the Japan communications ministry unveiled ambitious goals under its "Beyond 5G" strategy, seeking to capture a 30 percent global market share for base stations and other infrastructure, up from just two percent at present.

NTT DOCOMO's research and development of 5G evolution and 6G technology seeks to realize technological advances in several areas, including the following:

- **The simultaneous implementation of several key communications requirements such as ultra-high-speed, high-capacity, and low-latency connectivity**

- **The pioneering of new frequency bands including terahertz frequencies**
- **The expansion of communication coverage in the sky, at sea, and in space**
- **The provisioning of extremely low energy and low-cost communications**
- **The guarantee of extremely reliable communications**
- **The developing of capabilities for extremely massive connectivity and sensing**

3.3 European 6G Efforts

Europe has also moved forward with variety of different 6G initiatives spanning government and academia.

3.3.1 European Commission

On March 20, 2020, the European Commission unveiled plans to invest in 6G. The Strategic European Partnership will involve research and development in the field of smart networks and services beyond 5G/towards 6G, high-performance computing, quantum computing and critical digital and data cloud infrastructure.

The 6G Flagship project (referred to as "ICT-52" within the Horizon 2020 plan) includes details, such as:

- **Winning consortium will possibly consist of Major vendors, operators, universities, industry stakeholders**
- **Timeline: 2020-2023 vision and technology exploration**
- **Budget envelope of $1B from 2014-2021 for 5G through Horizon 2020, with a slightly lower estimate for 6G from 2022 to 2029 via Horizon Europe**

3.3.2 6G Genesis Flagship

On April 18, 2018, the Academy of Finland selected the University of Oulu to lead a new national research program on 6G. The 6G Flagship initiative consists of five collaboration partners, including Aalto University, Business Oulu, Nokia, Oulu University of Applied Sciences, and VTT Technical Research Centre of Finland Ltd. Two additional company co-creators include Keysight Technologies and InterDigital. In June 2019 ETRI (Korea) signed an MOU with the University of Oulu. The total budget for the 2020-30 Flagship program is 290M€.

https://www.oulu.fi/6gflagship/

The goals of 6G Flagship are to:

- **Support industry in finalization of 5G**
- **Develop fundamental technologies needed to enable 6G**
- **Speed up digitalization in society**

Research in 6G Flagship is organized into four interrelated strategic research areas

- **Wireless Connectivity**
- **Devices and Circuit Technology**
- **Distributed Computing**
- **Services and Applications**

In September 2019, 6G Flagship published a 6G white paper based on a workshop held in the first 6G Wireless Summit 2019 describing the 6G vision and key research questions for the development of 6G.

6G Flagship experts are leading 12 expert groups producing 12 new white papers

- **6G Drivers and the UN SDGs**
- **Validation and Trials for Verticals towards 2030's**
- **Machine Learning in Wireless Communication Networks**
- **Networking**
- **Broadband Connectivity in 6G**
- **RF & Spectrum**
- **Connectivity for Remote Areas**
- **Business of 6G**
- **Edge Intelligence**
- **Research Challenges for Trust, Security and Privacy**
- **Critical and Massive Machine Type Communication towards 6G**
- **Localization and Sensing**

Drafts were published on 30th April 2020 and found at https://www.6gchannel.com/

3.4 Korea Efforts

On January 28, 2019, LG set up a 6G Research Center at KAIST (Korean Advanced Institute of Science and Technology). The focus of the effort is to secure core technologies for 6G. (LG sets up 6G research centre at KAIST). Samsung also opened an Advanced Communications Research Center in Seoul to focus on 6G during early 2019. Samsung and LG Electronics are investing $800 million in setting up research centers in Seoul, South Korea.

South Korea Telecom (SKT) signed a 6G MoU with vendors like Nokia, Ericsson, and Samsung. Also, KT Corporation signed 6G research MoU with Seoul National University (SNU) in June 2019.

3.5 Taiwan Efforts

On April 29, 2019 Taiwan's Ministry of Science and Technology (MOST) initiated 6G academic research projects. (Taiwan moving to develop B5G, 6G tech)

4. How will Future Communications Change Beyond the 2020s?

4 How will Future Communications Change Beyond the 2020s?

This section as well as an area of the appendix section discusses a variety of possible use cases that are currently being discussed across the industry. These include scenarios promised in 5G networks, but not yet realized, and more advanced scenarios that are emerging in the context of next generation/6G networks. We describe these possible use cases from the customer or service point-of-view and do not restrict them to any implementation approach. As the industry evolves over the next several years these use cases are subject to change as the industry and the consumers future needs are better understood.

4.1 Use Cases

At a recent Northeastern University 6G Symposium on October 20-21, 2020, there was discussion on both use cases and technology evolution towards 6G. A main theme of the symposium addressed the merging of the digital, virtual, and physical worlds bringing new interface opportunities.

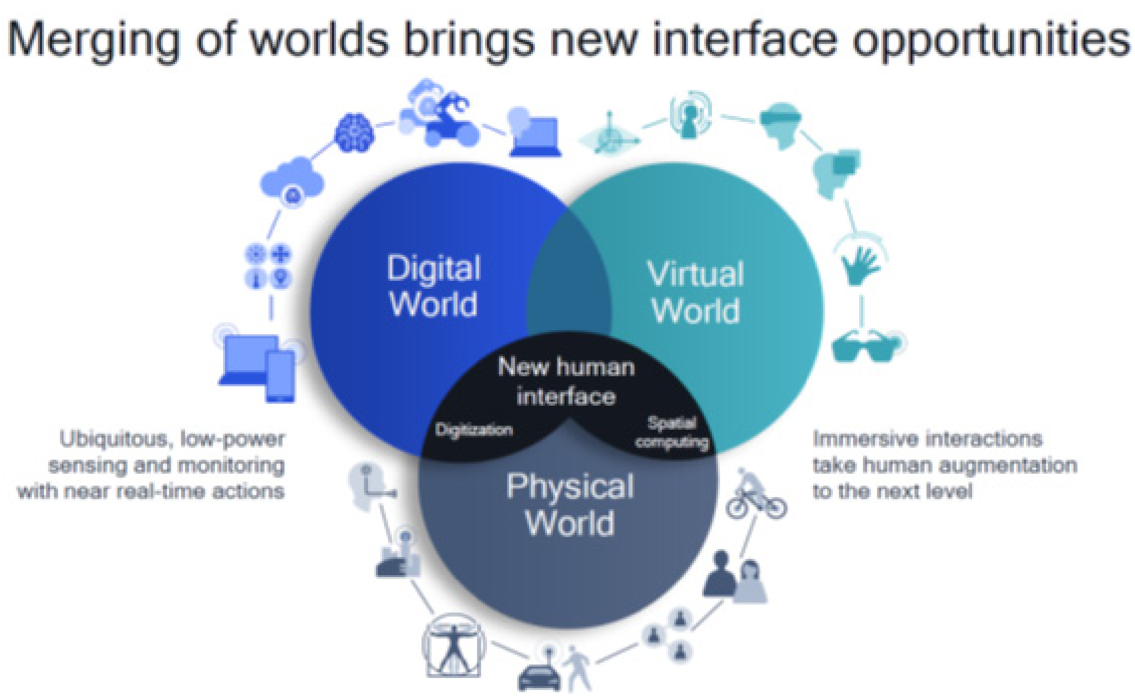


Figure 4-1 Merging of worlds brings new interface opportunities

Source: Qualcomm 6G Symposium, October 2020 used with permission

In addition, the symposium also addressed how 6G will evolve towards a more data-driven end-to-end wireless system.

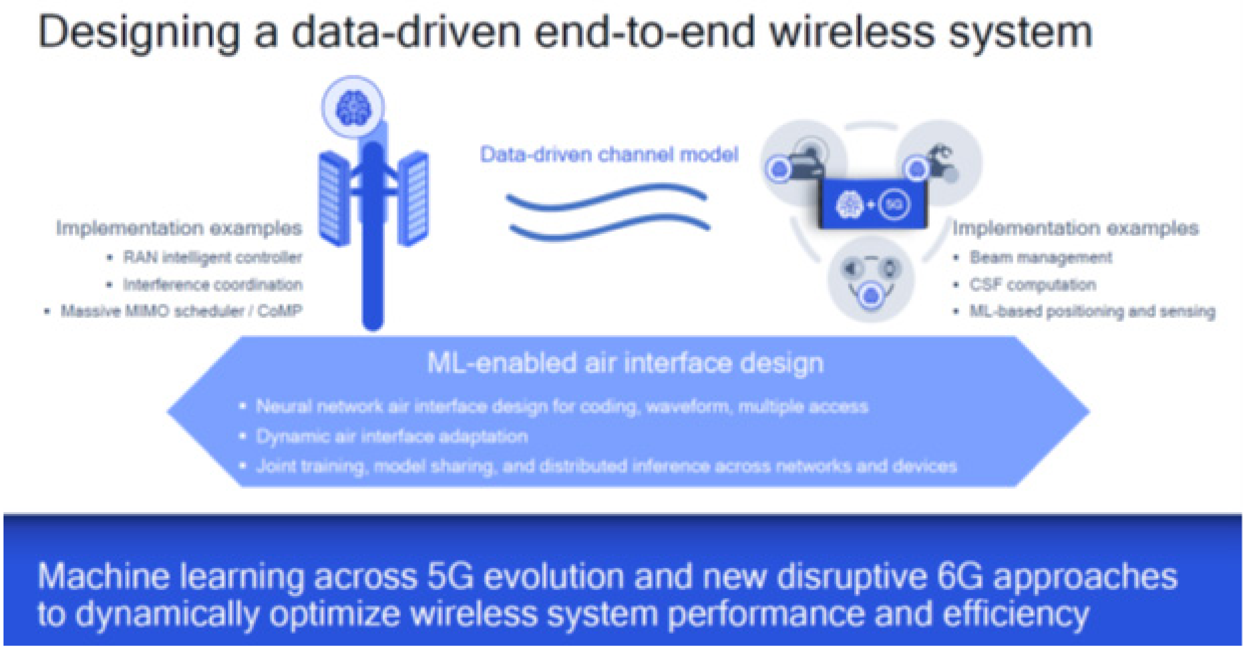


Figure 4-2 Designing a data-driven end-to-end wireless system

Source: Qualcomm 6G Symposium, October 2020 used with permission

Another aspect that the symposium focused on was how use-case scenarios are enabled by the network platform:

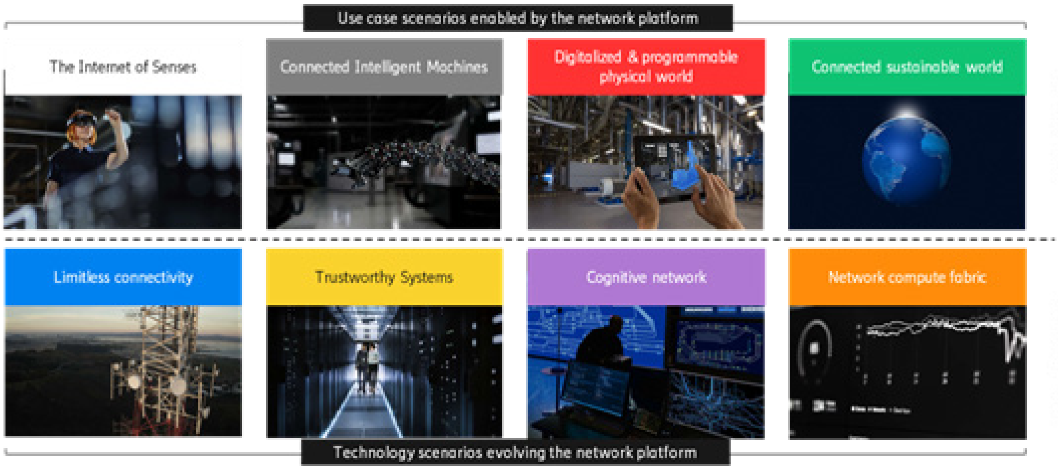


Figure 4-3 6G Technologies and their Use Cases

Source: Ericsson, 6G Symposium, October 2020 used with permission

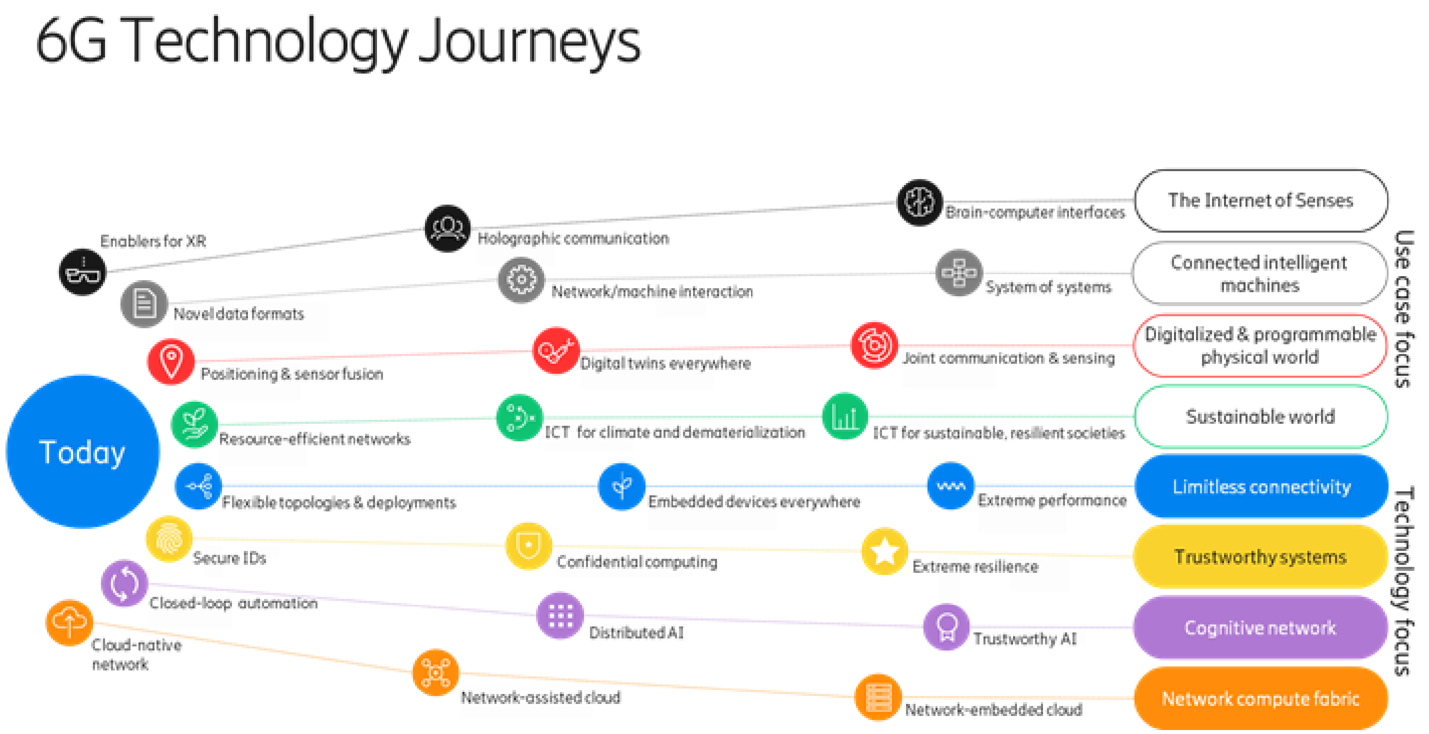


Figure 4-4 6G Technology Journeys

Source: Ericsson, 6G Symposium, October 2020 used with permission

According to presenters, the journey to 6G also leads towards an evolution to limitless connectivity:

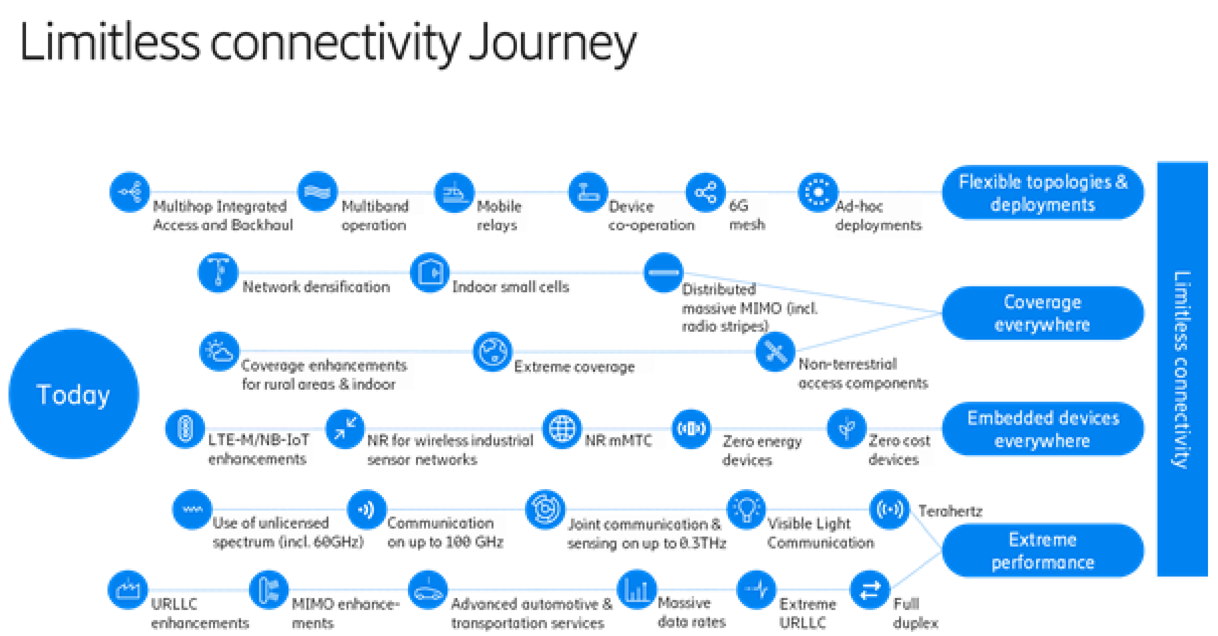


Figure 4-5 Limitless connectivity Journey

Source: Ericsson, 6G Symposium, October 2020 used with permission

4.1.1 Holographic Communications

Holography is a method of producing a 3D image of a physical object by recording, on a light-sensitive medium (e.g. photographic plate), the pattern of interference formed by a split laser beam where one of the beam paths interacts with the 3D object in question. The resulting interference pattern contains the complete optical amplitude (intensity), phase (depth) and wavelength (color) information that characterize a visual representation of any 3D object formed by the human brain. When the interference pattern is illuminated either with a laser or with ordinary light, the optical amplitude and phase information of the original object is regenerated, and the human brain perceives a realistic 3D picture of the original object.

Studies based on human perception of 2D images and conventional 3D videos that use binocular parallax technology to create 3D effect and holograms reveal that a holographic display comes closest to satisfying all visual cues for human visual observation of any 3D object. In other words, for humans, true holograms are the best substitutes for natural sight.

In the next decade, network advancements are expected to enable fully immersive user experiences virtually. A key component of the 'immersive' nature of user experience is the transmission of 3D holographic images from one/multiple sources to one/multiple endpoints in an interactive manner. There are a variety of user-device oriented technologies, such as the adoption of lenslet light-field 3D through the naked-eye, or AR/VR via head-mounted display (HMD) devices. However, fully immersive, and interactive 3D holographic imaging/streaming will be a challenge even for future networks.

4.1.2 Tactile/Haptic Communications

The Tactile Internet can be considered as the next evolution of the Internet of Things (IoT). The Tactile Internet encompasses human-to-machine and machine-to-machine interaction enabling a variety of real-time interactive and control systems applicable to industrial, societal, and business use cases. It adds a new dimension to human-to-machine interaction by enabling transmission of human touch and haptic sensations. This enables humans and machines to interact with their environment, while on the move and within a certain physical range over which communication takes place. The Tactile Internet may also revolutionize machine to machine interactions by building upon the next industrial revolution, Industry 4.0, with the addition of human interactions into the mix. If developed properly, the promise of this combination will be nothing short of revolutionary for how humans learn and work using the Internet.

Robotic surgery is one example of the Tactile Internet. At one end is the human system interface, which is a master console where the surgeon gets a real-time audio-visual-haptic feed of the patient and operating room. Additional data feeds such as patient diagnostics and reactions are provided in real time. The visual feed is provided using real-time holographic streaming technology (mentioned above) with adjustments based on whether the surgeon is wearing a head mounted display device or interacting with a hologram. As the surgeon proceeds with the operation the haptic-enabled robots (Human System Interface) at the patient-end mimics the surgeon's actions with high reliability, fidelity, and minimum latency. Realtime feedback (audio/visual/haptic/patient diagnostic) from the patient side is transmitted back to the surgeon throughout the surgery process.

Another example is remote industrial management that involves remote real-time monitoring and control of industrial machinery. Remote control is enabled using tactile sensors providing kinesthetic feedback from the machine to the operator. Tactile feedback is augmented real-time audiovisual information, possibly using holography/VR technologies. To complete the closed-loop control, as with the surgery example above, diagnostic information—in this case from the machine/tool under remote operation control—is also fed back to the operator in real time.

The Tactile Internet use cases generally comprise real-time interactions that require the network to have very low end-to-end latency and guaranteed high bandwidth support. True interactive control in the Tactile Internet requires stringent synchronization between various data feeds. These network requirements will be explored in a later section.

4.1.3 Ubiquitous Services (Land, Air, Space, Sea)

This use case provides seamless service coverage nearly everywhere: all terrestrial, marine, air, and space-based locations. A seamlessly integrated connectivity framework consisting of land, sea, air, and space-based nodes would be a significant step forward compared to today's fragmented scenario. Potential advantages include:

- **Globally ubiquitous Internet access spanning every corner of the world including sparsely populated terrains, remote oceans, mountainous regions, various airborne mobile platforms, space-based assets, etc. This represents a significant expansion of the current reach of broadband Internet predominantly in populated areas.**
- **Ubiquitous edge services (caching, computing, storage, etc.) capabilities**
- **A rich diversity of connectivity pathways allows for next generation routing protocols with the potential for significant improvement in network performance compared to today's primarily/solely terrestrial-based Internet protocols. Note that today's air/space-borne network assets are primarily used as relays for point-to-point connectivity between two terrestrial nodes.**
- **Enable new network connectivity topologies with 'z' axis added to today's surface-based (x-y axes) routing infrastructure**
- **Enable new services, for example, real-time 3D visual display of terrain in the immediate path of moving platforms**
- **Extend real-time emergency visibility and response to every remote corner of the world that until now were entirely cut-off from current emergency response infrastructure.**

4.1.4 Medical/Health Vertical

A transformative healthcare experience in the 21st century will need the confluence of multiple innovations spanning across all aspects of the healthcare industry. 6G has the potential for being the technology driver for enabling these innovations and fundamentally reshaping this critical vertical sector for future generations.

Many countries' healthcare systems suffer from numerous shortcomings—lack of ubiquity (access/quality/cost); little/no seamless coordination between service consumers, providers, or underwriters; lack of closed-loop interactive remote monitoring; rudimentary telemedicine (especially in remote areas where the need is the highest); and disjoint medical data privacy rules and/or implementations. Exacerbating the problem is a rapidly aging global population that is creating a huge burden on respective national healthcare systems that appears to be only increasing with time.

A variety of IoT-based approaches for personal health monitoring and reporting (temperature, pulse rate, glucose levels, blood pressure, etc.) are now on the market. However, current consumer-grade wearables are primarily used for preventative measures. In the future, these devices will be sufficiently accurate and reliable for diagnostic purposes but may require frequent updates from central repositories and may suffer from low battery life. To carry data from such devices would require a network that is power efficient, more responsive (i.e. lower in latency and jitter), and reliable even at higher throughputs. Today's smartphones do not always have the proper connectivity, and therefore cannot be used for some of these applications due to liability concerns. For widespread adoption, not only are high grade monitoring devices required, but also a high-performance, reliable, secure, and ubiquitous communication infrastructure.

In addition, for telemedicine, especially for remote telesurgery performed by either human and/or robots, the underlying data transport must satisfy stringent and demanding requirements for reliability, fault tolerance, bandwidth, latency, jitter, and embedded AI. While 5G could meet some of these requirements, 6G is expected to be the first communication infrastructure capable of handling 'full spectrum' healthcare needs of the 21st century.

While it is likely that 5G will make progress in meeting the overall needs of 21st century telemedicine use cases, it may not be sufficient to handle all scenarios. We will likely need 6G for the telemedicine vertical to achieve its full potential. At a high level, the following enhancements would be necessary for the complete transformation of next generation healthcare:

- **Enhanced radio interfaces and access beyond previous generations of wireless communication to enable massive increase in system capacity (spectral efficiencies, antenna gains, etc.), ultra-low latency, ultra-high resiliency, fault tolerance and continuous ubiquitous availability**
- **RAN virtualization and distributed cloud computing on a global scale**
- **IP transport optimized for ultra-high bandwidth, ultra-low latency, ultra-high resiliency, fault-tolerance, and continuous ubiquitous availability**
- **Seamless coordinated Network Slicing capabilities to enable global reach of specialized transport ("Healthcare" slice) under roaming scenarios that involve multiple operators, MVNOs, and IPX providers**
- **Real-time machine learning analytics for self-optimizing/organizing/healing networks**

4.1.5 Government/National Security

Mobile networks are also becoming part of a critical national security strategy where governments see a need for advanced communication technologies and ubiquitous connectivity to operate with speed, precision, and efficiency.

Governments want to deploy their national security enterprise networks more quickly and with lower cost. Governments see the possibility of efficiency gains, rapid deployment, and adaptation of their facility operations with automated vehicles and logistics with future networks ready to deploy anywhere, anytime.

National security requirements for future networks call for ubiquitous high-speed connectivity for moving massive amounts of data in dense networks and for low-latency communications to enable new generations of unmanned and autonomous systems, both in the air and on the ground.

Effective and survivable future networks must operate in contested environments with constant threats and counter with new capabilities. Spectrum sensing systems will classify signals to detect denial-of-service attacks and self-organizing radio access networks will dynamically use the spectrum to continue operations unimpeded. Future networks must counter attacks on data traffic and control elements with national security-specific enhancements not found in commercial networks today, including robust network protocols and air interfaces with low-probability of intercept and detection.

Figure 4-6 Future networks to serve national security use cases with speed, precision, and efficiency. [11]

The U.S. Department of Defense (DoD) is a major government/national security stakeholder in mobile telecommunications beyond 2020. Seeing no end to the possibilities with 5G, the DoD strategy for the future network emphasizes “5G to Next G” [10]. Today, this strategy considers 5G as transformational, bringing not just new radios and cell phones, but wireless “ubiquitous connectivity” for human-to-human, machine-to-machine, and human-to-machine. A secure “5G to NextG” system must operate through adversarial impediments by incorporating zero trust precepts.

The U.S. DoD partners with industry to understand and influence 5G to Next G use cases, expecting to gain commercial industry advantages while mitigating vulnerabilities unique to the DoD. Figure 6 below illustrates a wide array of DoD use cases and highlights the initial tranche of prototypes (circled in red) that DoD and industry will be evaluating.

Figure 4-7 5G Use Cases for DoD, highlighting those being prototyped today

4.1.6 Use Case: Imaging and Sensing

Novel sensing and image applications will drive the continuing demand for more communication-based applications and leverage the Future Networks to serve them.

Smartphones today employ imaging and sensing applications for ultra-high-definition video recording, ambient light detection for optimizing display quality, and accelerometers and gyroscopes to measure motion and orientation. The advent of 6G opens the possibilities of extremely novel sensing and imaging applications, e.g., through mmWave and THz radio technology, either employed in smartphones, IoT devices, or 6G base stations.

New sensor types within future smartphones could detect body gestures and monitor personal health without a user touching the device. IoT devices and smartphones could sense chemicals and allergens in food and drink and alert on air quality and precise levels of harmful gases. 6G base stations, along with their role in communication infrastructure, could act as geographically distributed sensor networks that could sense changes in the surrounding environment. Through their sensing they could, for example, enable use of smart city services for street traffic management, pedestrian crossings, etc. [37

New use cases of imaging techniques become possible by illuminating objects and scenes with short mmWave and THz wavelength signals and capturing their reflections, all at angular and ranging precisions not seen today. Real-time indoor 3D imaging combines with mixed reality systems to feed augmented and virtual reality applications. Vehicles would see through fog and rain to form images of the surrounding traffic and the road ahead.

4.1.7 First Responder/Emergency Services

Public Safety (PS) with Emergency Service Response (ESR) requires a reliable (availability, reliability, and resiliency), ubiquitous, network agnostic communication framework providing voice, data, and video, and other emerging communication technologies. ESR operations cover maritime, aerial, and terrestrial environments. While initial work on such 5G services began in 3GPP Release 15, further enhancements over several release cycles are expected. For example, the baseline architecture would need to incorporate situational awareness, building on existing location services including longitude, latitude and altitude, collection of data rapidly from sensors, known assets and other sources to synthesize with AI-based responsive analytics to provide meaningful data analysis of situations and share data securely in regards to personnel, asserts, threats, and hazards in a manner suitable to providing emergency service operations.

When considering mobile networks for emergency communications, several parameters are critical: network redundancy, on-demand/temporal coverage, in-building solutions, location centric capacities, failure scenarios such as network outage with rapid recovery solutions and alternate communication recovery solutions (satellite backhaul, Mobile network On Wheels (MOWs). Complete communications must be in place in order to provide operational capabilities for services for applications such as Mission Critical Push-to-Talk, battery powered System on Wheels (SOWs), battery powered System on Backpacks (SOBs) with communication relay capabilities, as well as Device-to-Device (D2D) communications. Furthermore, as seconds can cost lives, ultra-low latency communications with ultra-speed high throughput data transfers and on-demand bandwidth capacities are essential requirements from emerging or future networks for emergency services.

Non-human autonomous or remotely controlled network connected assets such as drones, connected vehicles, and robots are essential to complement human first responder emergency services. The following diagram captures an envisioned network system for first responder emergency services personnel when and where it is needed:

Figure 4-8 Envisioned emergency services network

Some of these necessary capabilities can be illustrated with the specific use case of Concentrated Localized Video Large Talk Groups, which requires on-demand capacity.

As most emergency situations are localized to a particular location, a video talk group (similar to a conference call, but in a push to talk mode) of at least 3000 members consisting of police, fire, ambulance - Emergency Management Technicians [EMT], and an Emergency Management Control Center (EMCC) can be supported. This will allow visual feedback in multiple angles to all participants of the talk group to instantaneously analyze and respond to the emergency. One or two cell towers can usually support the aerial bandwidth access requirements. Using technologies such as Enhanced Multimedia Broadcast Multicast Systems (eMBMS) with the capability to switch broadcast feeds dynamically can be an alternative solution. Finally, live video (stored and forward) transmission via network connected body cameras and from police vehicles to dispatcher control centers, where the camera can be remotely controlled.

4.1.8 Cyber-Physical Systems/Manufacturing

Throughout the course of history, the world's technology has evolved over time and has been characterized by several epochs, paradigm shifts or revolutions. At present we are transitioning from the 3rd Industrial Revolution to the 4th Industrial Revolution. This 4th revolution is being characterized by the emergence and proliferation of Cyber-Physical Systems (CPS). Cyber-Physical Systems marry the digital world with the real world. It is enabled by technologies that bring the virtual and physical worlds together and where intelligent objects communicate and interact with each other. As previously mentioned, one example of CPS is the Massive Internet of Things (MIoT), which represents connectivity and interaction between a massive number of physical objects.

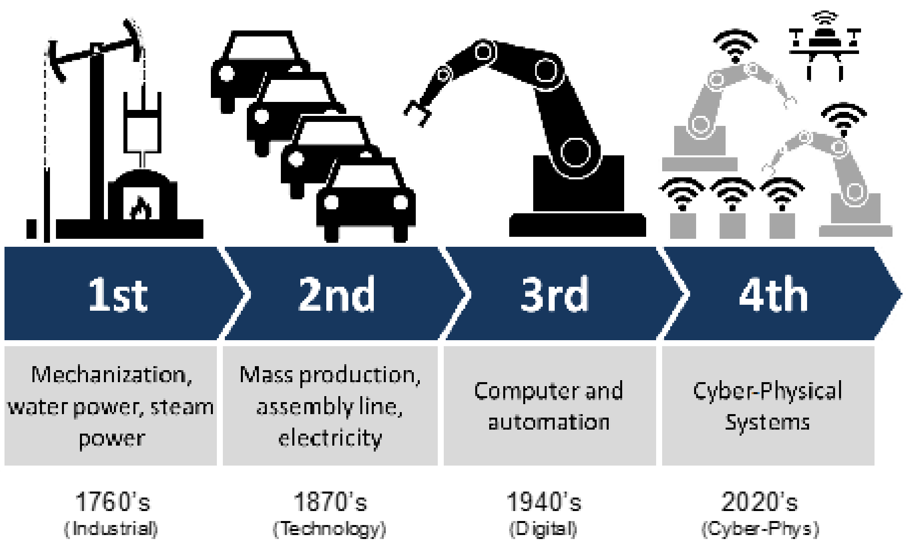


Figure 4-9 Industrial Revolution

Another example of CPS is the concept being called Industry 4.0—a combination of automation, data exchange and machine intelligence aimed at manufacturing technologies. Note that Industry 4.0 is not the same thing as the 4th Industrial Revolution, but Industry 4.0 does depend on the Cyber-Physical Systems envisioned as part of the 4th Industrial Revolution. Industry 4.0 has also been referred to as a "smart factory" or a "lights-out factory," an industrial environment that can run semi- or fully autonomously. The term "lights-out" means that the factory can function without any humans being present, therefore it can operate 24/7 and has no need for traditional lighting.

One aspect of Industry 4.0 is the ability to collect information, share information and use that information to make better decisions (in a decentralized way) and be more productive. Industry 4.0 also uses the concept of a digital twin (described in section 4.1.3) to create a virtual copy or model of the physical world, and this twin allows the system to test changes and make decentralized decisions before being implemented the real world.

4.1.9 Transportation Vertical

Transportation is the backbone of the modern society and represents a large percentage of the GDP for some countries. For example, the transportation industry contributed $1.2 trillion USD in 2018 and accounted for roughly six percent of the U.S. GDP [37]. The future communication system would greatly boost autonomous driving, while a smart transportation infrastructure would greatly improve the entire transportation system's efficiency, productivity, and safety.

5G systems can already be considered to support many transportation use cases [38][39], with V2X (Vehicle-to-Everything) communication technology [40], including Vehicle-to-Network, Vehicle-to-Infrastructure, Vehicle-to-Vehicle, Vehicle-to-Pedestrian, etc. Over the next decade, with a predicted surge of Autonomous Driving and Intelligent Transportation Systems, as well as use cases extending from vehicles to pedestrians and cyclists, new use cases and business models will likely emerge and bring new requirements to the underlying communication system [41]. Here, we list some promising use cases for the future transportation vertical market:

1) **Improving efficiency of transportation systems**
    a. **Car platooning**
    b. **Speed harmonization**
    c. **Smart intersections**
2) **Advanced Driver-Assistant Systems**
    a. **See-through**
    b. **High definition sensor sharing**
    c. **Real-time high definition maps**
3) **Improving transportation safety**
    a. **Left turn assist**
    b. **Vulnerable road user discovery**
4) **Autonomous Driving-related**
    a. **Remote driving assistant for autonomous vehicles**
    b. **Cooperative maneuver of autonomous vehicles**
    c. **Cooperative perception**
    d. **Cooperative safety**
5) **Intelligent Transportation Systems**
    e. **Faster emergency response and road operators**
    f. **Smart highways with autonomous driving lanes**
    g. **Dynamic traffic flow management**

3GPP Releases 15 and 16 have defined both a traditional Base Station-User Equipment (BS-UE) Uu interface and a peer-to-peer PC5 interface for V2X communication [40]. Those 5G systems are designed to support 10 ms end-to-end (E2E) latency, 1 ms physical (PHY) layer latency and 99.999% reliability [40].

As new use cases like autonomous driving and smart transportation increase over the next decade, the speed of vehicles may increase well beyond today's limit that is designed for human drivers, such as going beyond 100 miles per hour. The general rule of thumb for inter-vehicle distance (for instance, two seconds to impact), could also be largely reduced - thereby further improving traffic efficiency. Collaborative communication and computing among nearby vehicles and mobile edge computing nodes would also boost new location based, latency sensitive services that could bring intelligence to the transportation system.

Under these new scenarios, the coordination among autonomous vehicles, human-driving vehicles, pedestrians, transportation infrastructure like traffic lights, roadside units, and mobile edge computing nodes will require even lower latency. For instance, we may see requirements such as up to 1 ms E2E latency, or 1/10 ms for the PHY layer, with 99.99999% reliability in ultra-high density environments of tens of thousands of mobile or stationary nodes squeezed within a square mile area - with or without cellular network infrastructure support. Even today's sophisticated 5G V2X solutions are probably unlikely to deliver the required latency, reliability and vehicle density needed for such use cases, and hence a new network evolution will be needed.

4.2 Use Case Analysis – Technology Requirements

This section collects the technical requirements and capabilities needed to deliver the use cases described in Section 4.1. These are service level requirements and capabilities, which are intended to be independent of any particular implementation approach. More specific approaches and solutions are pursued later in Section 5 . In general, this white paper attempts to quantify the minimum capabilities whenever possible, and it is not uncommon for a single use case to demand several requirements or capabilities to be fully deployed. Finally, Section 4.2.9 provides a summary table that maps technology requirements to use cases.

4.2.1 Very High Bandwidth

It is expected that next generation systems will require enormous increases in bandwidth. As a comparison, going from 4G to 5G could enable up to a 10-fold increase in bandwidth. The IMT-2020 requirements for 5G are 20Gbps for aggregate peak downlink (DL) and 10Gbps for aggregate peak uplink (UL), while minimum end user speeds are 100Mbps/50Mbps (DL/UL) [13]. While 5G users can expect speeds in the hundreds of Mbps, this will be insufficient for some use cases such as holographic communications and cyber-physical systems. Estimates for high fidelity holographic immersive services range from 0.5 – 1.0 Tbps [14]. In the case of wireless data centers, they will require individual links with close to 1 Tbps data rate per processing rack and flexible interconnect within multiple rows of racks with extremely low latency requirements.

Similarly, Digital Twins, Tactile/Haptic Communications and related Cyber-Physical Systems require bandwidth in excess of 100Gbps for non-holographic immersion and, in addition, require a fast uplink due to the need to send information from device back to cloud [15].

4.2.2 Very Wide Coverage

Wide area coverage is one of the strengths of cellular networks and is expected most of the time by users. Typically, users have grown accustomed to small pockets of weak coverage encountered due to the vagaries of the radio environment. However, for some use cases, even small pockets of weak coverage cannot be tolerated. These next generation use cases rely on uniform coverage over large geographic areas. Massive IoT networks and Smart Agriculture and

Livestock with sensor devices spread out over large areas like cities, farms, and roadways. In addition to providing uniform coverage over large areas, Ubiquitous Services must be provided in new remote areas not previously served at all (e.g., outer space and across entire oceans). Such services will create a seamless integrated connectivity framework consisting of terrestrial (land-based and marine), airborne (pseudo-satellites, aircraft, balloons, drones) and space-based (LEO/MEO/GEO satellite constellations) infrastructures.

4.2.3 Enhanced Reliability

Next generation systems will also require higher levels of network reliability. The minimum reliability requirement for 5G is described as the successful probability of transmitting a 32-byte L2 packet in 1ms to be $1\text{-}10^{-5}$. However, this requirement will be insufficient for next generation use cases such as telesurgery other health related services (see 4.1.6), industrial remote control/digital twins modeling applications, transportation vertical, (see section 4.1.15), and national security/government services. These demanding next generation services require reliability and redundancy that approach "seven 9's" availability (99.99999%) [15].

4.2.4 High Density of Endpoints

The proliferation of an increasingly larger number of endpoint devices in an area has a two-fold impact on network requirements. First, the sheer number of devices can hamper the ability of the radio access network (RAN) to support connectivity to all these devices. Second, this large quantity can impact the ability to efficiently manage the signaling and operational overhead of numerous endpoints, leading to low revenues per endpoint.

Already, 4G and early 5G networks can support millions of endpoints. Since each device roughly corresponds to a paying customer, the overhead of using existing architectures can be tolerated. However, new services like massive IoT are pushing the requirement of networks to support millions or even billions of additional simple endpoint devices in limited geographic areas, where the revenue per device is much lower than that of current customer devices. This places additional burden not just on the RAN architecture, but also impacts signaling loads and overhead associated with service provider activities for on-boarding, authenticating, operating, maintaining subscriptions, and managing numerous low revenue devices. Early 5G networks can be expected to support up to 1 million devices per square kilometer [13]. But emerging use cases will demand device density to increase tenfold up to 10 million devices per square kilometer [16].

While the aggregate traffic demands of these mIoT devices are manageable, the networks of the future will need mechanisms to support the very high density of endpoints in a cost-effective manner with minimal network overhead. This overhead includes RAN connectivity, the signaling load per device, and operator processes to manage these low revenue devices. While modern networks have made improvements, even in early 5G systems, the overhead to support these endpoints remains too high. New capabilities are needed for the mobile operator to better cope with next generation high endpoint density services.

4.2.5 Synchronization of Multiple Flows to Multiple Devices

Legacy end user applications usually consist of a single traffic flow directed at a single device. However, emerging use cases such as AR/VR and holographic communications are expanding this to encompass multiple simultaneous traffic flows where the arrival of packets must be synchronized. These services will require synchronized parallel media streams to arrive to the user for a proper service experience. For multi-modal services like tactile/haptic communications, this includes different types of streams, e.g., corresponding to different human senses. Such service streams may originate from different points in the network. And finally, the different service streams might be destined to multiple endpoint devices in different locations but synchronized, nonetheless. Therefore, new mechanisms are needed to ensure quality of service in delivery across a disjoint set of service flows.

4.2.6 Time Sensitive Operations (Bounded Latency and Jitter)

To provide the ultimate experience of delay-sensitive real-time applications, such as interactive tactile/haptic communications, latency-related performance needs to significantly improve. Time-sensitive operations for services related to digital twins, transportation vertical require zero packet loss due to buffer congestion, extremely low packet loss due to equipment failure, guaranteed upper bounds on end-to-end latency, and extremely low fluctuations in packet transfer rates (delay jitter). Jitter would be a new key performance indicator for 6G that quantifies the latency variations in the system. Targets in 6G are envisioned to be air interface latency less than 10 ns, end-to-end (E2E) latency less than 100 μs, and extremely low delay jitter in the order of microseconds. [17] [18]

4.2.7 Precise Location Tracking

For advanced 5G and beyond use cases, the role of "location services" grows into the precise location tracking of objects in the vicinity of the user as well as tracking the device location. For the device, this includes real time and precise location and orientation tracking of headsets, glasses, or other user devices (including in some cases, the user's head), vehicle tracking, tracking along six degrees of freedom for AR/VR services, as well as tracking for holographic communications. (In other words, next generation systems will require tracking along the three dimensions of movement (x,y,z) plus pitch, yaw, and rotation.

4.2.8 Extremely Low Power and Resource Constrained Devices

While early 5G networks have methods to lower the power or battery requirements on IoT devices, some future services such as massive scale IoT, may require devices to operate on extremely low power. This may even take the form of some devices never needing to be charged (e.g., absorbing energy from its environment). Such devices must have new ways to interact with the network in a manner of minimal energy usage. In addition to power usage, other resources such as memory, compute and storage may be very limited in the device. This may require modifications to some of the procedures and protocols used.

At the same time, security for communication and security at the application level remains vital for all devices. These considerations must be balanced with the resource limitation of constrained devices.

4.2.9 General Industry Requirements

The key design principles of Industry 4.0 are:

Interoperability

- The ability of machines, devices, sensors, and people to connect and communicate with each other via the Internet of Things (IoT) or the Internet of People (IoP).
- Adding IoT will further automate the process to a large extent.

Information Transparency

- The ability of information systems to create a virtual copy of the physical world by enriching digital plant models with sensor data. This requires the aggregation of raw sensor data to higher-value context information.

Technical Assistance

- The ability of assistance systems to support humans by aggregating and visualizing information comprehensibly for making informed decisions and solving urgent problems on short notice.
- The ability of cyber physical systems to physically support humans by conducting a range of tasks that are unpleasant, too exhausting, or unsafe for their human co-workers.

Decentralized Decisions

- The ability of cyber physical systems to make decisions on their own and to perform their tasks as autonomously as possible. Only in the case of exceptions, interferences, or conflicting goals, are tasks delegated to a higher level.

Industrial applications have very demanding requirements with extremely tight tolerances. This is because of the speed at which these machines operate, and the amount of uninterrupted data required to either make decisions about actions or perform actions as instructed. At present, specialized protocols or variants of Ethernet (termed “Industrial Ethernet”) are being used to meet the bandwidth, latency and reliability needs of machines on the factory floor.

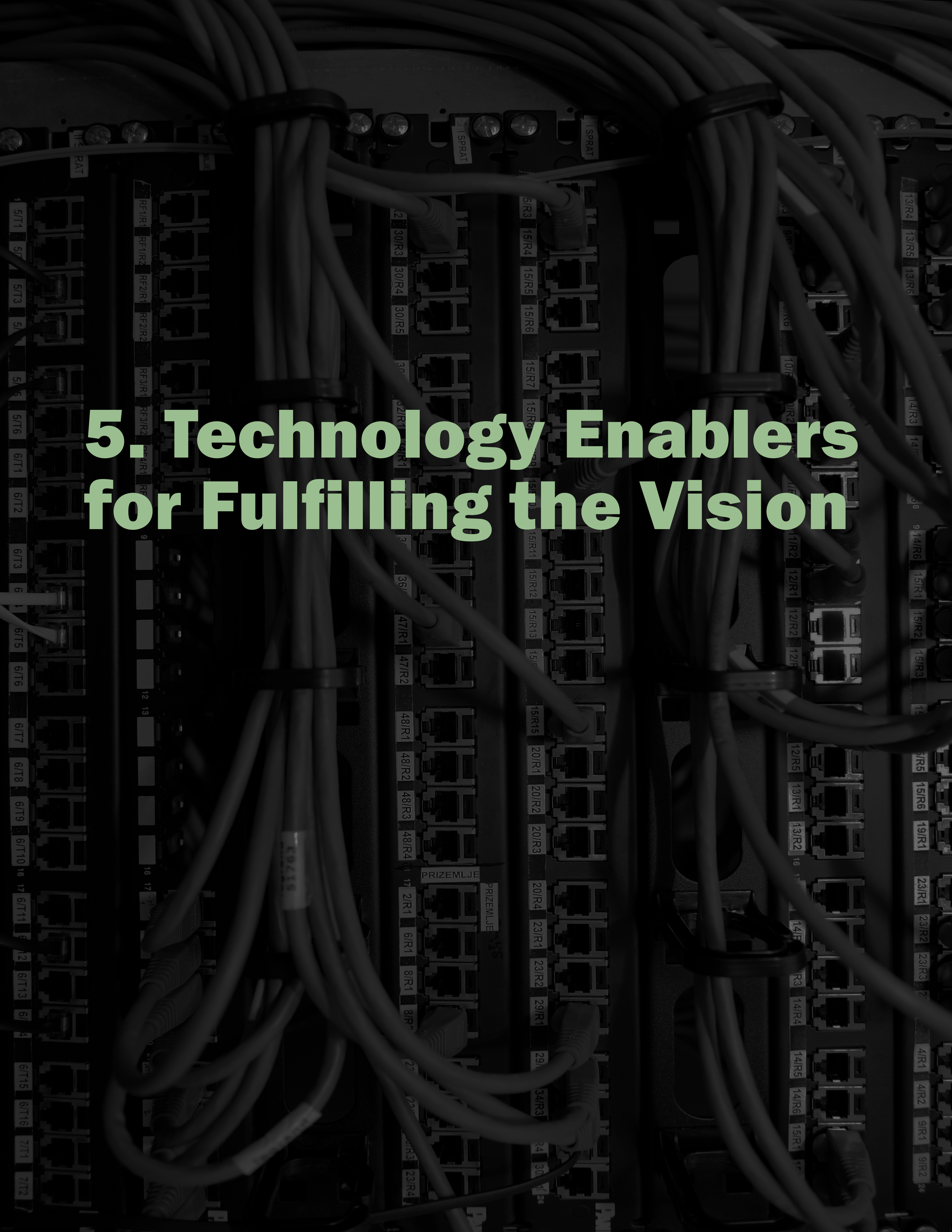
5G conceptually includes high bandwidth (eMBB), low latency (URLLC) and high density of device connections (MMTC). But for industrial applications, the amount of bandwidth and the density of devices will be continuously increasing along the continued need to reduce latency. 3GPP Release 17 has begun addressing Enhanced Industrial IoT, and 3GPP Release 18 is likely to continue to study Cyber-Physical Systems (CPS). As has typically been the case with 3GPP architectures, these features and the extent of their tolerances are on an ever-improving continuum. Current 5G definitions lack the machine learning and artificial intelligence (ML/AI) capabilities required to predict failures, trigger maintenance, and operate autonomously. By integrating improved bandwidth, latency and density with ML/AI, the next generation of network can go beyond what is envisioned today to a scalable and implementable CPS solution.

4.2.10 Summary: Use Cases to Tech Requirements

Technology Requirement	Use Case(s)	Notes
4.2.1 Very High Bandwidth	4.1.1 Holographic Communications 4.1.2 Tactile/Haptic Communications Appendix - Digital Twins	BW 0.5 – 1.0 Tbps
4.2.2. Very Wide Coverage	4.1.3 Ubiquitous Services Appendix - Massive Scale IoT Networks Appendix - Agriculture & Livestock	Gbps coverage everywhere with new coverage areas, e.g., sky (10000 m), sea (200 NM), space etc.
4.2.3 Enhanced Reliability	Appendix - Augmented Reality/ Virtual Reality/Mixed Reality Appendix - Digital Twins 4.1.2 Tactile/Haptic Communications 4.1.4 Medical/Health Appendix – Telesurgery 4.1.5 Government/National Security 4.1.7 First Responder/Emergency Services 4.1.9 Transportation Vertical	“seven 9’s” availability (99.99999%)
4.2.4 High Density of Endpoints	Appendix - Massive Scale IoT Networks Appendix - Smart Agriculture & Livestock	10 million devices/km^2

4.2.5. Synchronization of Multiple Flows to Multiple Devices	Appendix - Augmented Reality/ Virtual Reality/Mixed Reality 4.1.1 Holographic Communications Appendix - Digital Twins 4.1.2 Tactile/Haptic Communications Appendix - Telesurgery	synchronized parallel media streams, originating in different points of network
4.2.6 Time Sensitive Operations	Appendix - Digital Twins 4.1.2 Tactile/Haptic Communications Appendix - Telesurgery 4.1.9 Transportation Vertical	air interface latency $<$ 10 ns, E2E latency $<$ 100 μs Jitter order of μs
4.2.7. Precise Location Tracking	Appendix - Augmented Reality/ Virtual Reality/Mixed Reality 4.1.2 Tactile/Haptic Communications 4.1.9 Transportation Vertical	Six degrees of motion: (x,y,z) plus pitch, yaw, and rotation
4.2.8. Extremely Low Power and Resource Constrained Devices	Appendix - Use Case: Massive Scale IoT Networks Appendix - Smart Agriculture & Livestock	Extremely low power including devices never to be charged (e.g., absorbing energy from its environment)
4.2.9 General Industry Requirements	4.1.8 Cyber-Physical Systems/ Manufacturing	

5. Technology Enablers for Fulfilling the Vision



5 Technology Enablers for Fulfilling the Vision

This section provides examples of concrete technical approaches or solutions that satisfy the technology requirements collected in Section 4.2 and stemming from the use cases listed in Section 4.1. This paper anticipates that these technology enablers, or something similar, will be necessary to fulfill the needs of next generation networks.

5.1 Artificial Intelligence at the Network Edge

As artificial intelligence turns out to be an important resource to enable more powerful services across several use case categories, the necessity of artificial intelligence at the edge of the network is becoming clearer.

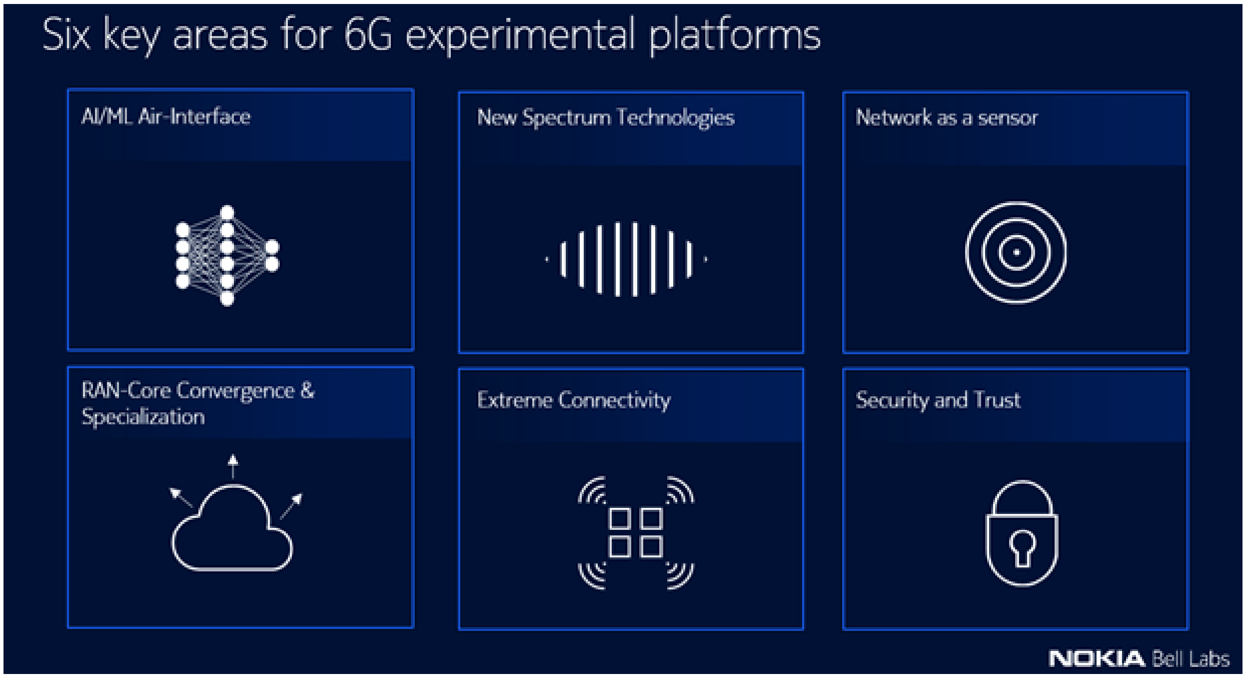


Figure 5-1 Six key areas for 6G experimental platformsSource: Nokia, 6G Symposium, October 2020 used with permission

For many use case categories, whether they support millions of low bandwidth devices on a massive IoT network, or networks with high bandwidth devices such as video cameras, enormous data sets will be created at the edge of networks. Reducing the need to transport these data sets to a central location requires intelligent processing at the edge. AI can be used to extract useful patterns and events out of a sea of raw data. For example, smart farming applications can spot dry patches or insect infestations while a video surveillance system can pinpoint areas with suspicious looking activity.

If a use case demands AI processing and a real-time response to be effective, the network cannot rely only on centralized AI resources. An example is when an AR system requests real-time visual object recognition in the current environment. XR systems that have real-time interactions with remote, virtual, and real objects place high data rate/low latency/computation intensive demands on networks. Furthermore, it might be advantageous to pre-process an AI model in the device itself and then distribute further AI capabilities across the edge and central locations. This results in more flexibility between the intelligence of devices, edges, and central resources.

Training AI models usually require time spent to collect the data for machine learning models, training these models, and defining actions based on the learned models to be returned to the application. Some use case categories such as mission critical applications demand accurate responses within a very short response time. V2X systems controlling sets of platooning vehicles that are interacting with other traffic and pedestrians is such an example. These kinds of cases benefit from the use of pre-trained models deployed at the edge along with additional dynamic online learning at the edge.

Privacy rules in certain cases will drive some data to remain very local at the network edge. To take advantage of AI capabilities on this data entails using online distributed training algorithms that can be employed at the edge or even rely on data storage in the edge devices themselves.

5.2 AI/ML in the RAN

AL/ML concepts and technology can be expected to have major impact on RAN systems evolution. Due to better level of performance and reduced complexity, they have the potential to replace some of the model-based Layer 1 and Layer 2 algorithms such as channel estimation, preamble detection, equalization, and user scheduling. AI/ML will be applied extensively in deployment optimization on the road towards zero human touch network optimization, for example for configuring an optimal subset of beams with which to illuminate the coverage area, taking cell traffic patterns into account.

However, next G systems can be envisioned to employ AI/ML in a more fundamental way - namely AI as a foundation for air interface design and optimization. Next G communication framework will be designed in such a way as to allow learning in the field to make some design choices. Through extensive training, a single deep-learning network at the transmitter and one at the receiver learn to pick the best design. This will enable optimization of the air interface characteristics based on the choice of spectrum, environment, hardware deployed and target requirements. [22]

5.3 Fully Service Based – Cloud Native Networking and RAN-Core Convergence

In the 5G era, the transition to a cloud native and microservice-based architecture is a key change. Cloud native technologies empower service providers and vendors to build and operate scalable applications in dynamic cloud environments. A microservice provides a dedicated business function and is an integral part of a service-oriented architecture with published APIs and options for discovery. [19]

Beyond 5G networks are likely to be extreme-edge or edge centric and data flow-based across the network. Network functions and other workloads would be dynamically scheduled in a hierarchy of data centers across the network topology [20]. The criteria used to arrange the functions and workloads would be based on the combination of available resources, connectivity needs, latency requirements, energy consumption targets, etc. and would use AI & ML-based multi-object optimization algorithms to optimally balance the criteria. [21]

One of the most important dimensions of cloud native architectures is how they are delivered and orchestrated: the transition to the DevOps [22] paradigm will assure an agile framework for continuous delivery and integration for large scale digital production environments.

Research into the design options of the next G offers the opportunity to make the network simpler and more flexible. Latency, security, resilience, and energy efficiency can be used as criteria to optimize functional placement. Separation of user plane and control plane, virtualization and cloud native implementation of the core have facilitated the greatly increased level of flexibility. In this context, a profound transformation of the RAN can be expected with the separation of the base station CU control and user plane functions, cloud native implementation, and centralized placement; the service-based architecture approach of the 5G Core will extend to the RAN in the next G era. Because of increasing traffic volume and lower latency requirement, the core user plane functions will move closer to the edge.

There are additional opportunities to harmonize the RAN and core functions to create a simpler network. We envision that the next G network will essentially have a 'Lower Layer Function' entity that includes all the latency critical air-interface related RAN functions that are not included in the radio unit, and 'User Plane Micro Services (UPMS)' and 'Control Plane Micro Service (CPMS)' functional entities that include all the higher layer RAN and Core capabilities as micro-services. The CPMS includes both RAN and Core services such as radio resource control, radio intelligent control (RIC), mobility management, authentication, and radio resource management. The UPMS includes higher layer RAN user plane as well as core user plane services such as header compression, encryption, QoS policy enforcement and deep packet inspection. The UPMS and CPMS will be based on a framework that exposes APIs for new micro-services to be added to the core set of services that define the two functional entities. [18]

Subnetworks: There is also a great opportunity for semi-autonomous next G sub-networks with special attributes of performance, where at least the most critical services in the subnetwork will continue uninterrupted despite poor or no connectivity to the wider network. Multiple path connectivity employing infrastructure and opportunistic device-to-device connections will be required for the ultra-reliability, potentially leading to fully meshed and truly cell-less architectures. The integration of such sub-networks into next G architectural paradigm will ensure high data rates, extreme low latency, reliability, and resilience, while security and resilience features will be enforced to the lowest level of devices in the sub-network. Next G service execution can dynamically be split between execution in the edge cloud or in the device that is part of the sub-network. [18]

5.4 mmWave and THz Radio Technologies

Academia and industry are driving research into existing mmWave as well as greenfield and unexplored THz spectrum to meet world-wide demand for mobile communications and applications. At these new frequencies lie an opportunity for a tenfold increase in the amount of spectrum available today [23, 24].

The US Government showed its support for this research in 2019 when the FCC opened the 95 GHz to 3 THz frequency range for experimental use and by reserving selected bands for unlicensed applications. This FCC action represents the emergence of this greenfield spectrum for 6G (Figure 5-2).

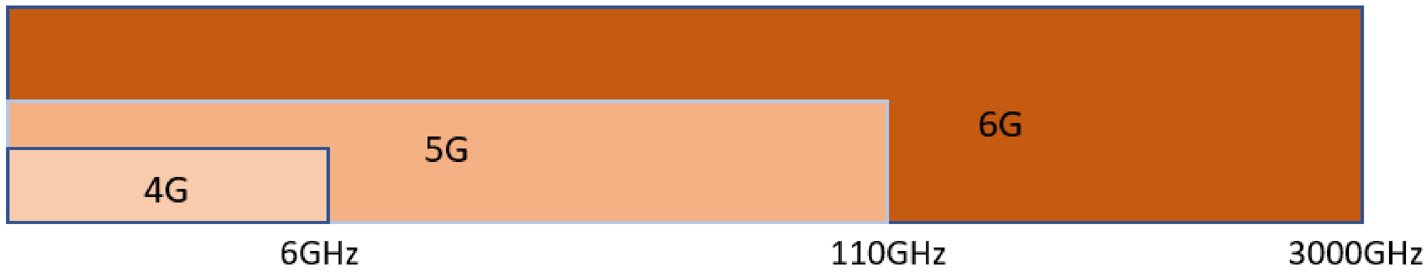


Figure 5-2 Spectrum Usage for Different Generations [17]

The capabilities of this extended spectrum goes beyond today's 5G capabilities and enables new 6G use cases. The immense bandwidth available in the mmWave and THz regions add orders of magnitude higher data rates for terabit/sec mobile communications and backhaul systems. The potential for massive spatial multiplexing also expands the volume data rate (bits/sec/m^3) for 3D multi-link connectivity [25]. The short wavelengths make for accurate sensing, imaging, spectroscopy [26] and pencil beams for highly accurate angular positioning. Low signal powers and high bandwidth radios can also form security bubbles for undetectable and uninterruptable communications for commercial and military applications [27]. Extremely low power consumption radios become possible by closely locating mmWave and THz transmitter and antenna components [25].

Operating above 110 GHz

But getting into this greenfield spectrum requires many beyond-leading-edge capabilities that make 6G radio technology uniquely distinct from earlier generations [17]. The challenges span the mmWave/THz air interface and the transport and processing of signals at terabit/sec speeds.

The following table captures the various air interface challenges and the proposed beyond-leading-edge technical capabilities to overcome these challenges.

Table 5-1 Air interference challenges and proposed solutions

Greenfield Air Interface Challenges	Beyond-leading-edge technical capability
Severe path-loss and atmospheric absorption	Antenna gains from ultra-massive MIMO with accurate, practical THz multipath channel models.
RF front-end, photonics, and data conversion	Power efficient, mW capable semiconductor technologies based on InP, GaAs, SiGe, and CMOS.
Antenna, lens, and beamforming architecture	Metamaterials to block, absorb, enhance, or bend electromagnetic waves at THz frequencies.
Reduce peak-to-average power ratio (PAPR)	New waveforms to support GHz-wide channels.
Lower complexity and remain effective for THz operation	New signals, channels, and protocols.

Transporting and processing the THz signal poses even more challenges that need to be overcome, including low loss between antenna and integrated system, proper heat dissipation, low power data conversion (analog-to-digital/digital-to-analog) with digital input/output at Tbps data rates. [17]

R&D needed for today's 5G mmWave radio systems

While basic research is under way for the future of 6G, the R&D community today is squaring up to tackle the technical challenges to evolve 5G mmWave, sub-THz, and densified networks.

mmWave systems R&D: Ongoing research in mmWave systems focuses on the support of a large number of antenna elements with commensurate narrow beamwidth beams, form-factor user equipment (UE) design considerations, and attendant cost, die size, power, thermal and real-estate challenges. From a UE design perspective, the design metrics bring the focus on good spherical coverage and good spectral efficiency. Finding optimal placement of multiple antenna modules at the UE will overcome the coupling and coexistence challenges from other radiating elements at the UE [28]. The current set of beam management techniques based on hierarchical beamforming [29, 30, 31, 32] must evolve to reduce latencies, power consumption and thermal overhead. Given the higher power consumed by the mmWave radio relative to sub-6 GHz frequencies, a research problem of immense interest is the design of an efficient sleep-wake up cycle. Further challenges comprise machine learning/artificial intelligence-based beam management approaches taking advantage of prior history to make better predictions of likely good beam candidates. However, such approaches need to evolve over existing beam management techniques instead of taking a greenfield view of beam management and, more importantly, lead to reduced power consumption after including the cost and energy associated with the use of the prediction algorithm.

Sub-THz systems R&D: A significant amount of ongoing research to improve mmWave systems will benefit sub-terahertz systems. Initial product design in this greenfield spectrum will follow the approach established in mmWave systems today. For instance, implementing new radio frequency integrated circuits (RFICs) with on-chip or on-board antenna arrays.

Of the many challenges in the design of sub-THz systems, a key problem is UE power consumption. Simply scaling the power demands of mmWave systems to account for 100s of Gbps data rates results in unrealistically high-power consumption. Therefore, 6G will have to provide much better performance than 5G in terms of information bits transferred per Joule expended. As bandwidth is abundant at sub-THz frequencies, the traditional paradigm of trading off processing power with utilized bandwidth can be changed by the use of new PHY waveforms and flows, design of new channel codes which tradeoff spectral efficiency for better power efficiency, new antennas inspired by optical lens designs to potentially lower RF power requirements, new approaches for beam management and channel equalization, and new RF front-end designs to improve efficiency of elements like PAs and LNAs for the new bands.

The higher frequencies associated with narrower beamwidths lead to reduced interference, increased latencies in beam acquisition, increased power consumption, and higher thermal overheads. Use of larger bandwidths leads to beam squinting effects that need to be addressed at the system level. Maintaining spherical coverage guarantees at higher bands can also become challenging due to poor radiative capabilities of antenna structures in a form-factor UE design [33]. In terms of RF Front-End power efficiency, as the frequency increases, the power efficiency of CMOS transistors decrease, possibly requiring the use of non-CMOS semiconductor solutions [34]. Furthermore, synthesizer phase noise is expected to increase in the higher bands and limit the highest spectral efficiency that can be achieved.

Densified networks R&D: To overcome coverage holes in mmWave and sub-THz deployments, densified networks are envisioned with smart repeaters and relay nodes. However, the cost-complexity-power-performance tradeoffs of such intermediate nodes needs to be fully understood. Densification of networks can serve as a natural realm for the study of artificial intelligence-driven approaches for scheduling, interference coordination and mitigation, and beam and link adaptation. These approaches can allow the personalization and tailoring of solutions for specific user profiles and behaviors (e.g., traffic shaping, route optimization, sleepy networks, etc.) and sharing learned experiences with other nodes via federated learning mechanisms.

5.5 Communications and Sensing co-design

Radio Detection and Ranging System (RADAR) is an emerging use case for LTE/NR or Beyond 5G / 6G wireless communications systems. The transmit signal of the radar system is reflected by the target (e.g. a human or a car), and by processing the received signal to derive properties such as distance, posture, velocity, and/or size of targets within range of the radio base station. [35]

RF-based sensing at high carrier frequencies will provide more accurate techniques to measure the environment, detect and recognize objects. The wider spectral range will provide opportunities to sense and identify new kinds of targets and variables which are not detectable in currently used frequency bands [36].

The combination of sub-mm Wave and the use of frequency selectivity to determine relative electromagnetic absorption rates is expected to lead to significant advances in wireless sensing technology. Generally, higher frequency bands allow very fine resolution in all physical dimensions: range, angle, and Doppler shift.

A separate system for sensing/imaging in addition to the communication system incurs additional infrastructure expenses that can be avoided if the communication system is also able to perform sensing and imaging. The mmWave/THz multi-band radio heads can serve multiple users across frequencies, perform RADAR, imaging, or sensing at multiple frequencies, or any combination at the same time. Aside from RADAR applications, a radio head can perform spectroscopy-type analysis. The variation between the received signal across frequencies from the radio head may reveal the differences between the material compositions in the field-of-view of the radio head.

One way to enable joint communication and short-range sensing is to use the “normal” downlink signal as the excitation signal, for example the OFDM resource elements in a system based on OFDM transmission such as LTE or NR. In this way, the short-range sensing can be enabled in some sense “for-free”, i.e. without having to assign network capacity specifically for this purpose.

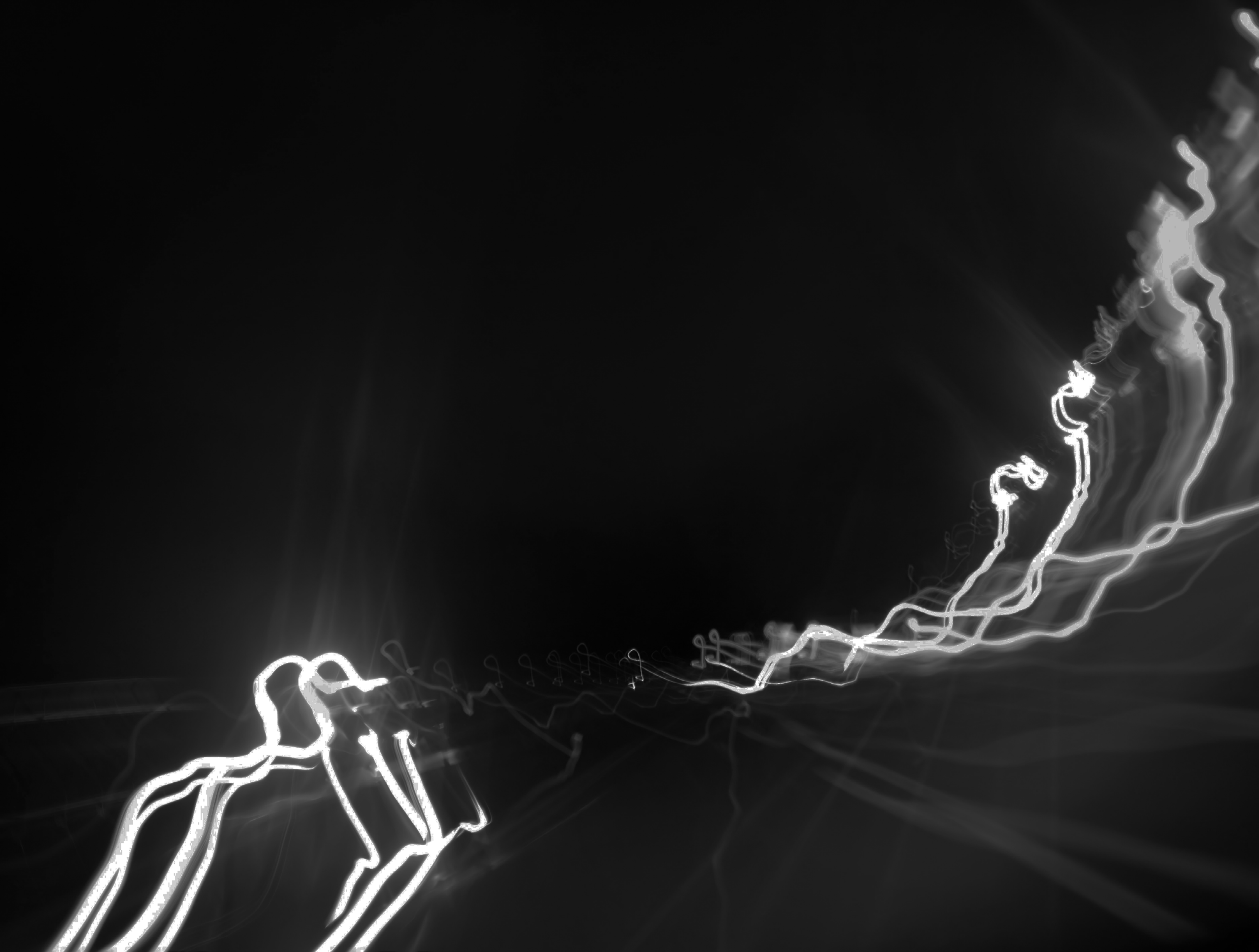
The RADAR excitation signals must be transmitted on all beams to obtain a full image of the covered area. A beam-based air interface having very large antenna arrays (mMIMO) can be leveraged for forming narrow beams that can be periodically swept; this procedure is called a beam sweep. In addition, with more granular beams and antenna arrays, it is possible to have multiple transmitters and receivers in a small space; a key to enhance the sensing capabilities. New channel charting methods based on AI/ML techniques applied to large antenna array systems will improve accuracy of sensing.

5.6 Spectrum Migration

The very high frequency bands of 6G technology must co-exist with the technology in lower frequency bands. As discussed in Section 5.3, the extension to very high sub-THz and THz frequency bands is considered for 6G. This can be viewed as a continuation of the 5G extension into mmWave bands. In the future, lower frequency bands will continue to be the wireless connectivity backbone for wide-area coverage. So like the 5G extension into mmWave, extensions to very high frequency bands is a complement to lower frequency bands by providing extreme traffic capacity and extreme data rates through very dense deployments.

Due to the limited availability of commercial sub-THz and THz spectrum, and as the main part of the available commercial spectrum is already in use by 4G and 5G technologies, it is important that a new 6G radio-access technology co-exists with earlier technologies in a similar way 4G and 5G co-exists today, for example by means of dynamic spectrum sharing.

6. North American Leadership



6 North American Leadership

In order to support the growth and development of next generation networks, North American companies should commit resources and time to allow members to lead this work and support each company's commitment. Leadership opportunities exist in both chairing, as well as taking on other leadership positions in organizations with a focus on leading the industry in the quality of contributions and in the essential intellectual property rights (IPR) of the work. Leadership can be exercised through demonstrating industry expertise, as well as taking the opportunity to publicly discuss the vision from North America and how companies are leading this technology effort.

6.1 Goals and Ongoing Activities

As growing non-North American influence in international standards setting processes is considered by some to pose national technology sovereignty risks, many North American leaders wish to ensure that the stage is set for North American leadership in 6G. To gain leadership in 6G, exploration beyond 5G kick started with Next G alliance creation. The alliance's mission involves developing technologies, architectures and drive global standards through joint R&D and expert working groups. Research could be the main focus area of the 6G Alliance in the immediate years with a focus on implementation after 2025 or so.

As North American companies begin to show their desire to gain technology leadership in the next generation of wireless cellular networks, there are several additional areas where these activities are becoming more visible. One area revolves around the opening up of the Radio Access Network (RAN) ecosystem. For instance, the following organizations are reflective of the growing North American desire to evolve 5G networks and beyond:

- https://www.o-ran.org
- https://www.openranpolicy.org/
- https://sites.atis.org/wp-content/uploads/2020/05/Promoting-US-Leadership-on-Path-to-6G.pdf
- https://nextgalliance.org/

6.2 Public-Private Partnerships

Public-private partnerships (PPP) usually involve a contract between two or more public and private sectors, which brings benefits such as:

- **access to funds**
- **access to technology, people, and skills**
- **shared risks and responsibilities**

To expand the public funding for research and development of emerging technologies, a 6G public private partnership could be developed. Such a PPP could include goals like the following:

- **aim to secure North America's leadership in the areas where North America is strong and where there is potential for providing novel 6G application capabilities in "vertical" sectors, such as automotive, healthcare, smart factories, smart cities, education, media & entertainment, thus creating a new ecosystem**
- **reinforce the North American industry to successfully compete on global markets opening innovation opportunities**
- **maintain and enhance the competitiveness of the North American ICT industry and to ensure that North America can enjoy the economic and societal benefits these future networks will bring**

These ideas and organizations could be modeled after similar structures already developed in for existing PPP's found elsewhere. For instance, below is the 5GPPP reference setup in Europe:

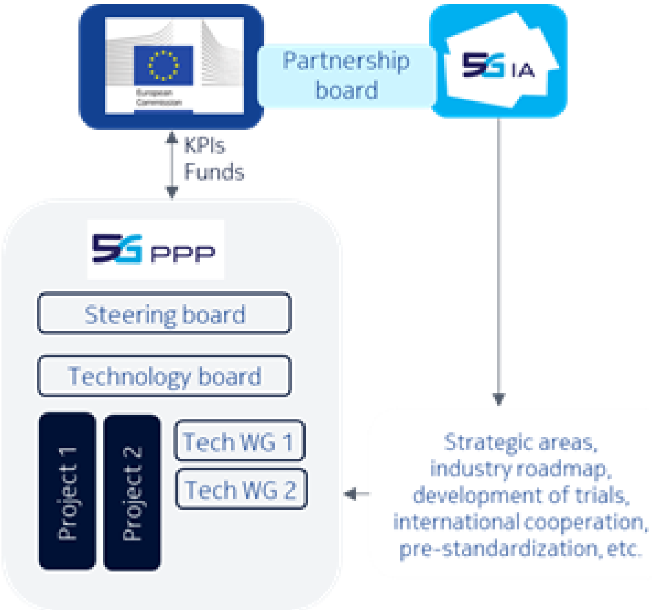


Figure 6-1 5GPPP Organization

The 5G Public Private Partnership (5G PPP) is the 5G collaborative research program that is organized as part of the European Commission's Horizon 2020 program – The European Union Program for Research and Innovation. 5G PPP is a partnership between EU and Industry to enhance impact through co-ordination across research projects. It is a contract between public (EU) and private (5G IA) defining the funding level, key objectives (KPIs) and associated research and innovation roadmap. The 5G PPP delivers solutions, architectures, technologies, and standards for ubiquitous next-generation communication infrastructure.

In the 5G PPP, the 5G Infrastructure Association (5G IA) represents the private side and the European Commission the public side. 5G IA is an Industry Alliance of operators, manufacturers, research institutes, universities, verticals, and SMEs. It consults the EU on Calls for Proposals based on industry roadmap and gets involved in evaluations. The 5G IA carries out a wide range of activities in strategic areas including standardization, frequency spectrum, R&D projects, technology skills, collaboration with key vertical industry sectors, notably for the development of trials, and international cooperation.

In North America, the Next G Alliance (or other similar organization) could influence U.S. government funding priorities and possibly set up the foundation for emerging technology vision, technology trends and its road map. Though there are ongoing foundational 6G research within academia and technology companies independently, multilateral research collaboration is beneficial for North American technology leadership. Next G Alliance could also provide the avenue for funding agencies such as DoD, Defense Advanced Research Projects Agency (DARPA) to offer technology priorities to influence research road map. When larger scale funding is available for 6G research, 6G collaborative research projects with many industry partners could be envisioned.

6.3 Standards

While it is expected that the standards work on the next generation will happen in global organizations like ITU and 3GPP, North American companies can continue to drive vision, scope, and insight into this work in different ways. North American companies can continue to be active as individual members in 3GPP, and actively engage in the US delegation in ITU and submit and work together on objectives as a group. These companies can also continue to support the needed research ahead of the actual standards process. The North American ICT industry can work together to drive an innovative vision of the future through organizations like 5G Americas or others that advocate for the industry.

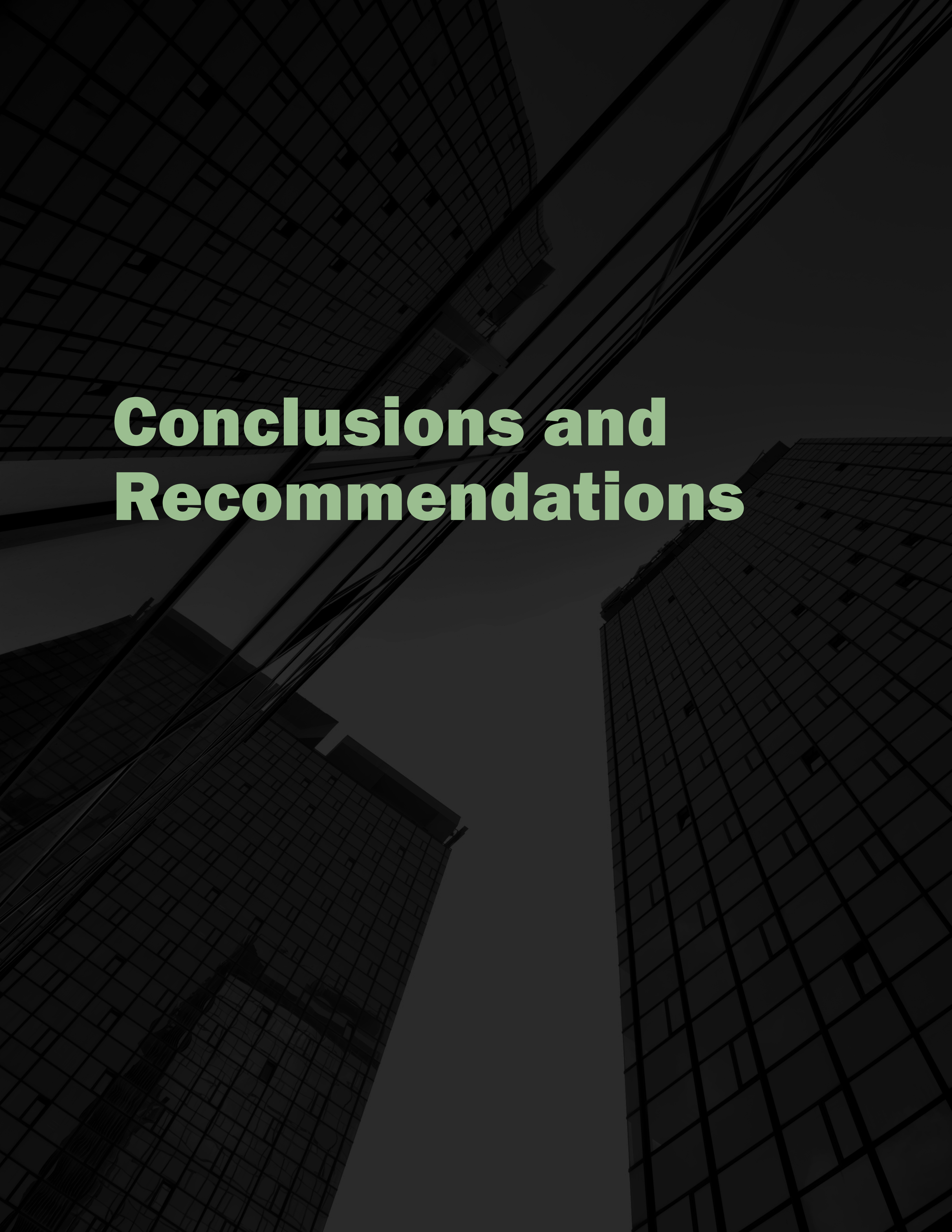
From a leadership standpoint, 5G Americas feels that North American wireless cellular and ICT companies should take the initiative instead of allowing other countries, regions, and organizations take the lead. Our organization believes, in particular, North American technology companies can do more to actively commit resources to push this work and to lead and participate in these global organizations in order to support them and continue to drive an innovative vision. 5G Americas believes there may always be situations when companies may not agree however having common goals and visions will be helpful to ensure the viability of next generation wireless networking.

7. Regulators in North America Help Industry Maintain Leadership

7 Regulators in North America Help Industry Maintain Leadership

North American regulators can continue to work with the mobile wireless networking industry to identify opportunities to attain technology leadership while balancing regulation. Streamlining cell cite processes, Private Public Partnerships and opening up access to more commercial use of exclusive use licensed spectrum, are examples regulator and industry opportunities. Regulators can help by promoting identified opportunities while minimizing government regulation and management of mobile technology.

Conclusions and Recommendations



Conclusion and Recommendations

This paper provided an overview of the industry research across the globe looking at the evolution of mobile wireless data networks. While many are already calling it “6G”, (but whatever it is called), it is still the evolution of 5G and beyond. Today, there is not a clear picture or definitions of 6G, so instead of arbitrarily categorizing technologies into “Gs”, we focused on the evolution of 5G towards an eventual next G.

In reviewing the use cases laid out in section 4.1, a global view is undertaken since these views are not necessarily unique to the Americas. Although 5G may meet many of these use cases and services, it is the continued evolution of these use cases that will require the industry to evolve and adapt beyond 5G and into the next G. 5G Americas recommends the innovative North America mobile wireless industry take action ensuring leadership in this great industry for decades to come.

Appendix

Appendix

Additional Use Cases

As stated throughout this white paper, the 5G technology architecture continues to evolve to meet the demands of new services of society. The mobile wireless industry is in the early stages of considering and addressing the many use cases enabled by wireless technology. Section 4.1 identified many of these possible use cases which may require further evolution of 5G and even new technologies that will be enabled by 6G. Whereas many use cases can be supported in both 4G and 5G, the enhancements being envisioned for 6G will even further enable many existing and new use cases.

The appendix below provides additional use cases that are being identified for the mobile wireless industry to address both today and tomorrow.

Wireless Networks in Data Centers

The exponential growth in demand for cloud services experienced over the last decade is expected to continue and even accelerate in the 2020s. The accompanying increase in the size and complexity of data centers and their internal network topology call for augmenting traditional fiber optic communications with wireless solutions. Fiber optics, while offering state of the art data rates, require considerable investment in expensive and bulky infrastructure and have limited reconfigurability once installed. Wireless solutions may offer much better flexibility and will be able to augment the networking inside data center, with the potential of opening existing bottlenecks, improving connectivity and provide the flexibility required for dynamic demands, bringing savings in power demands and infrastructure.

Digital Twins

A Digital Twin is a virtualization model of a physical process, product, or service—a real-time representation of a physical entity entirely within the digital domain. This pairing of the virtual and physical worlds allows analysis of data and monitoring of systems to predict performance, anticipate problems before they occur to minimize downtime (predictive maintenance), improve situational awareness, develop and test new scenarios for future application—all accomplished by using simulations in the digital domain.

Digital Twin technology can be applied to various scenarios. An example use case is advanced manufacturing. The ultimate goal is to create, test, and build equipment in a virtual environment and only when that equipment performs to exact specifications (in the virtual environment) will physical manufacturing be allowed to start. Once manufactured, the physical build would be linked to its Digital Twin through sensors so that the Digital Twin contains all the information that its physical counterpart possesses.

Another notable use case scenario for Digital Twin technology is Smart City planning. A modern city is a dynamic complex system composed of people, processes, services, events, infrastructure, etc. Using a Digital Twin model of the real city—with real-time feedback from physical to virtual domains—makes Digital Twin a powerful tool for operation, planning and evolution of future smart cities.

The underlying networking requirements for enabling Digital Twins include bandwidth, latency, elasticity etc. and will be explored in a later section.

Telesurgery

To illustrate the technology issues involved in the healthcare vertical, let us explore one the most demanding use cases – telesurgery. Telepresence, achieved through MR, as a surrogate for physical presence is a critical component for telesurgery. Telepresence requires development in several supporting technologies, such as very high-resolution imaging and sensing, wearable displays, specialized processors, AI-enabled robots, drones, and most importantly, the next-generation of wireless networks. In combination these MR technology enablers achieve a sense of presence through real-time capture, transmission, and rendering of a 3D holographic representation of participants (both service provider and consumer), real-time bi-directional haptic/tactile feedback and movement of data captured by a variety of health monitoring sensors.

The fidelity of the representations created at geographically separated locations, combined with the overall safety reliability of the system, must meet a high bar for consumer confidence. Perceptual illusions created by MR devices and underlying communication infrastructure must convince participants that there are, effectively, no substantive differences between the real and virtual co-location environments.

The MR experience described above is likely to be delivered by head-mounted spectacles that project images directly on the retina with very high resolution, frame rate, and dynamic range. For telesurgery, the visual imagery will be supplemented, in real time and in synch, with feedbacks provided to other senses via earphones and haptic interfaces. The supporting technologies include:

- **Imaging devices such as light field, panoramic, depth-sensing, and 3D holographic cameras**
- **Multiplicity of biosensors for monitoring health conditions – pulse rate, blood pressure, EKG, neural scan, blood glucose, etc.**
- **Distributed computing involving specialized AI-driven processing and sensor fusion algorithms for 3D holographic computer graphics. These capabilities would likely be distributed among the underlying transport and edge networks as well as well as embedded in the monitoring devices**
- **Wireless technologies enabled with next generation high-precision positioning and ranging capabilities.**

Augmented Reality/Virtual Reality/Mixed Reality

Extended Reality (XR) technology offers another avenue for 6G's impacts. In actuality, a continuum of user experiences spans Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) described as follows:

- **VR:** Computer-generated stereo visuals which surround the user, entirely replacing the real-world environment around them. Real-time user interaction within the virtual environment is possible, whether through detailed interactions, or simply being able to look around within the environment.
- **AR:** Overlaying of digitally created content on top of the real world. The user can interact with both the real world and digital elements or augmentations.

- **MR:** By combining bits of VR and AR together, MR seamlessly blends the user's real-world environment and digitally created content, where both environments can coexist and interact with each other. Although MR may be a marketing term, it is generally understood to be the merging of live footage of things in the real world with digitally created footage from VR applications.

Collectively, AR, VR, and MR capabilities and combinations are called Extended Reality (XR). XR capabilities are useful in several different fields and are broadly applicable over a wide range of different applications.

Take health care for example. MR might be used to view and manipulate patient medical information in different settings. Contextual patient data visualization permits various medical staff in a hospital or clinic to seamlessly coordinate their patient's treatment as a team by accessing health records and medical charts.

MR can also be used to treat patients remotely. Remote care is beneficial to patients with reduced mobility or those that require frequent doctor appointments to easily obtain medical review and advice from their homes. MR can also be used for remote surgery assistance. A surgeon performs a procedure but communicates and collaborates with other remote surgeons. MR provides video of the surgery and all required medical information readily to all the parties. And of course, MR can be used to perform the entire surgery remotely, i.e., telesurgery

AR can be used in a complex manufacturing plant. For instance, technicians dispatched to solve a problem can look at a machine on the factory floor and see the status of machine components superimposed on top of the normal camera view. As the technician moves around, they can see the real time status and trends of the components, such as the flow rate through valves and the position of switches. The technician can select a component for more detailed information, including service manuals.

XR services place several rigorous demands on the network. For instance, real-time and precise location tracking of headsets, glasses or other user devices (including the user's head) is required in six degrees of freedom—three axis for body location (x,y,z) plus pitch, yaw, and rotation for body orientation. Visuals, video, or an AR overlay display requires sufficient resolution that translates into high bandwidth requirements. Some applications can benefit from ambisonic audio to wrap the user in a surround sound field that rotates based on the listener's orientation. To deliver this surround sound experience, XR demands multiple streams to multiple devices with each data stream expecting low levels of latency, packet loss, and jitter. Depending on the use, an XR service might require streams to multiple destinations.

While current 5G systems are already beginning to address the above demands with the assistance of Edge Computing, further enhancements are needed which may only be realized with next generation 6G technologies.

Massive Scale IoT Networks

There are numerous industry sectors and use cases that could benefit from massive scale IoT networks, including:

- **Smart cities sensors e.g. parking spots, trash, air quality, and utility meters**
- **Transport and Logistics: asset tracking**
- **Weather data collection**
- **Connected wearables**
- **Forestry: forest growth sensors**

To support massive IoT applications, initial 5G systems have already made some progress streamlining parts of the network and the air interface. This remains a key area for further 5G development and should remain a 3GPP focus for the near-term releases.

Overall, there remains several challenges that limit the growth of IoT deployments. For instance, a very large number of endpoints need to be managed in a cost-effective manner with minimal network overhead. Monetization of massive scale IoT networks may also provide many challenges, including identity management. This challenge includes the complete life-cycle management of network equipment and devices, when easy addition and removal of devices is considered.

Additionally, these devices are resource and power-constrained. In some cases, devices are required to have very low power consumption but at the same time a wide coverage area. It is also important to support security at the communication and application level, as these wide area networks will likely be subject to robust attacks, but that must be balanced with the limits of device constraints.

Smart Agriculture & Livestock

Large scale sensor and actuator networks used in the agriculture industry is another example of a massive scale Internet of Things network that relies on vast numbers of very inexpensive and resource constrained devices. The scaling issue here involves the management of the sheer number of connected devices, not the modest bandwidth demands of each device.

Farmers can reduce waste and enhance productivity with the ability to monitor field conditions from anywhere and automated machinery to perform recommended actions. Smart agriculture and livestock gives farmers the ability to foresee production output, while allowing farmers to plan for better product distribution.

Smart agriculture is an emerging concept for managing all aspects of farming and agriculture using modern information and communication technologies. It allows for enhanced control of the entire farming process via optimization of human labor through extensive automation resulting in better quality products with higher yields.

Additionally, “Precision Crops” refers to IoT-based approaches that make crop production more controlled by precisely targeting needed treatment of crop acreage as determined by machines in real time. The biggest difference from the classical approach of crop rotation is that precision farming allows decisions to be made with fine-grained accuracy, on the order of square meters, rather than for an entire field that are many tens or hundreds of acres in size.

“Precision Livestock” enables farmers to monitor the needs of livestock herds on an individual animal basis. Nutrition and care can be fine-tuned to individual animals thereby preventing disease outbreaks, optimizing growth, and enhancing overall herd health. Large farm owners can use wireless IoT applications to monitor the location, well-being, and health of their cattle. With this information, they can identify sick animals so that they can be separated from the herd to prevent the spread of disease.

Among the technologies available for present-day farmers are:

- **Sensors:** ubiquitous and varied for monitor/control functions especially sensors related to soil, water, light, humidity, temperature management
- **Software:** specialized software solutions that target specific farm types or use case agnostic IoT platforms
- **Closed Loop Connectivity:** use of cellular, wireless technologies
- **Location:** GPS
- **Robotics:** autonomous farm machinery
- **Data analytics:** standalone analytics solutions, data pipelines for downstream solutions

Acronyms

5G	Wireless Technology defined by the ITU-R IMT-2020 requirements
6G	A term loosely used to describe the next evolution of wireless technology beyond the current IMT-2020 or 5G.
AI	Artificial Intelligence
AR	Augmented Reality
CPS	Cyber-Physical Systems
DL	Downlink
DoD	Department of Defense
GPS	Global Positioning System
ICT	Information and Communications Technology
IMT	International Mobile telecommunications
IMT-2020	Requirements issued by the ITU Radiocommunication Sector (ITU-R) of the International Telecommunication Union (ITU) in 2015 for 5G networks, devices, and services
IMT-2030	The likely name for Requirements expected to be issued by the ITU Radiocommunication Sector (ITU-R) of the International Telecommunication Union (ITU) in the future for 6G networks, devices, and services
IoP	Internet of People
IoT	Internet of Things
IPX	Internetwork Packet Exchange
mIoT	Massive Internet of Things
ML	Machine Learning
MR	Mixed Reality
MVNO	Mobile Virtual Network Operator
NB-IoT	Narrow Band Internet of Things
NR	New Radio
PHY	Physical Layer
RAN	Radio Access Network
SBA	Service Based Architecture
SDO	Standards Development Organization
UL	Uplink
URLLC	Ultra-Reliable Low Latency Communications
VR	Virtual Reality
WIOT	Wireless Internet of Things
XR	Extended Reality

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Acknowledgments

5G Americas facilitates and advocates for the advancement and transformation of LTE, 5G and beyond throughout the Americas.

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