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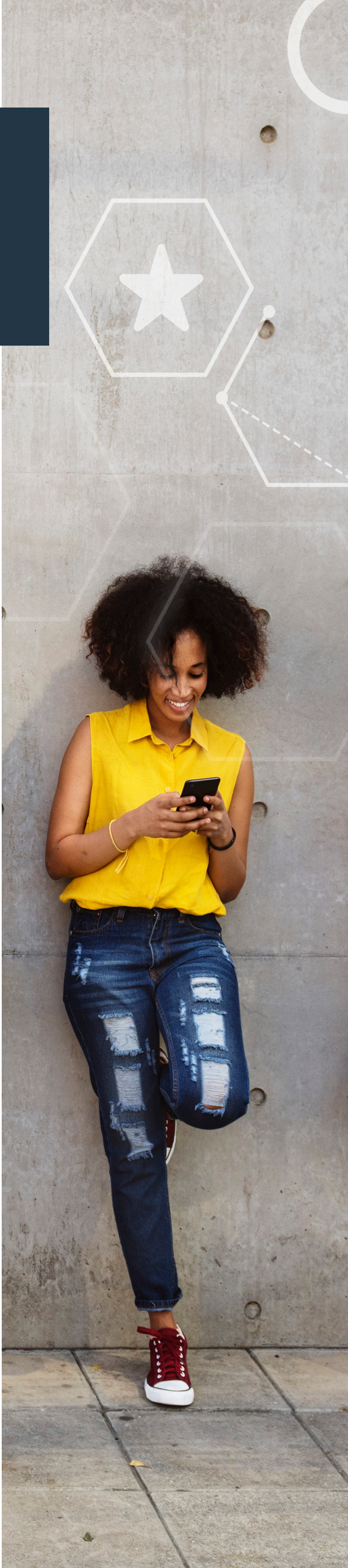
A 5G Americas White Paper

MOBILE COMMUNICATIONS TOWARDS 2030

Contents



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Executive Summary

As the world is beginning to enjoy the benefits of 5G, the “fifth generation” of wireless cellular technology, the industry is starting to plan sets of requirements needed for its continued evolution to 5G Advanced, as well as for the next generation of mobile communications. With each generation of wireless technology, the upgrade gets more complex and challenging. As we look ahead, 6G represents an even greater opportunity to extend wireless solutions into almost every facet of human and machine interaction. Additional enhancements and evolution of the current IMT-2020 (5G) technology standards have already started, just like it has been with all the previous “G’s”. The next G, “6G”, is still almost a decade away, but it needs to be defined now. The industry has been deploying a new G approximately every decade, and early discussions lead us to expect to have an IMT-2030 which can begin deployment around 2030.

For this reason, 5G Americas continues to review “6G” concepts from North America, Asia, and Europe and Latin America. The industry first must understand what is missing in 5G to create a 6G vision. There will be a requirement of establishing standards and several key technical challenges will need to be addressed. This 5G Americas white paper details technology requirements being discussed now by various industry stakeholders. The white paper provides an update on preliminary work being done globally on 6G and provides a few use cases and technologies for consideration for the evolution of 5G towards the next generation (next G)

From a use case standpoint, 5G Americas has identified early specifications and requirements for some use cases. We expect to see continued growth and demand for mobile communications 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 collaboration with other enabling technologies to change the world of connectivity. Moreover, the emergence of holographic communications, imaging and sensing, evolutions of massive IoT (mIoT), smart agriculture, and first responder services are presented in this paper in the context of the next generation technology.

This paper further evaluates technology trends and suggests how to enhance existing technologies towards the future evolution of wireless cellular networks beyond the current 5G. It emphasizes the need for extremely performant, trustworthy, intelligent, cognitive, flexible, and sustainable wireless communication NextG networks. 5G Americas understands that it is important to work towards exploration of technology enablers like AI/ML in RAN and edge, millimeter wave (mmWave) and terahertz (THz) radio, joint communication and sensing, spectrum sharing and coexistence, cloud native and service-based network convergence, communication, computing convergence, and more.

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, this white paper will identify necessary goals for North American companies and organizations in expanding leadership activities to further the development of future wireless networks.

1. Introduction

This paper addresses three main topics:

- *A review of activities beyond 5G in North America and globally*
- *How communications will change as we move towards 2030 and beyond, including many use cases and emerging technologies under nascent discussion and planning stages*
- *How North America can continue technical leadership*

5G is still early in its lifecycle and is being evolved and enhanced through upcoming 3GPP releases while worldwide deployment continues. As of September 2021, there are 184 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 demonstrated, this will probably be marketed as “6G”. ITU-R WP5D has begun development of vision and technology trends documents.

In addition, many projects identified as “Next G” and “6G” are already underway globally with significant leadership from the Americas. This paper specifically discusses the current view of potential new use cases, requirements and technologies. The government, commercial entities, and universities in the United States, through public-private partnerships, should actively engage 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 that this work will appear in a 3GPP release until after Release 19 or 20. It is expected to be ready for commercial deployment starting 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 networks. Other 5G Americas white papers have previously focused on other significant areas of 5G development, including: Vehicular Connectivity: C-V2X and 5G, Private and Enterprise Networks, Mid-Band Spectrum and the Co-Existence with Radio Altimeters, Future of Voice in Mobile Wireless Communications, 3GPP Releases 16, 17 & Beyond and Mobile Communications Beyond 2020 – The Evolution of 5G Towards Next G.

While users are just now coming to understand and utilize 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 will provide overview at the steps that North America as a region can take to achieve this leadership.

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. 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. Systems Design for Terabit Wireless Communications, IC Design for Terabit Wireless Communications, High-Performance Transistors for Terabit Wireless Communications, and Center-Wide Demonstration Vehicles are the research themes covered. Researchers at the UC Berkeley, UCSB, UC San Diego, Cornell Univ, MIT, NYU, Stanford Univ, UT Dallas, USC, Georgia Tech and Columbia University are heavily involved in this initiative.*
- *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.*
- *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.*
- *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 6G Symposiums in October 2020 and March 2021. Additionally, it held its Fall 2021 Symposium on September 21-22, 2021.*
- *Purdue University and the Purdue Research Foundation launched 'Lab to Life' (L2L) 6G digital innovation platform at Discovery Park District on August 24, 2021.*
- *University of Texas at Austin launched 6G@UT, a new research center to lay the groundwork for 6G, the next generation of wireless technology. Founding 6G@UT affiliates Samsung, AT&T, NVIDIA, Qualcomm and InterDigital and will develop wireless-specific machine learning algorithms, advanced sensing technologies, and core networking innovations that will be the backbone of 6G.*
- *Arizona State University is conducting research resulting in proofs of concept to demonstrate the possibility of 6G spectrum uses and features, focused on research areas like sensing, localization, large antenna arrays for devices, etc.*

Other universities working on 6G include the Georgia Institute of Technology, 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 the 2021 Summit was postponed. Their main research focus is application of radar for centimeter-precise telemetry, etc.*
- *Broadband Wireless Networking Lab of Georgia Institute of Technology is conducting research on terahertz-band communications and other 6G topics.*
- *The University of Arizona Wireless Communications and Networking Laboratory (WICON) is actively involved in the areas of wireless communications, networking, and security, with particular emphasis on resource allocation strategies, distributed protocol design, and security. Recently, the group has been involved in projects related to 4G/5G cellular systems, mmWave protocols (beamforming, initial access, phased antenna arrays, wireless backhauling, etc.), cognitive/agile radios, dynamic and shared spectrum access, harmonious coexistence of heterogeneous wireless systems, full-duplex transmissions, ultra-low-latency mobile edge computing (MEC), network slicing, physical-layer wireless security, satellite communications, MIMO systems, energy management in wireless sensor networks, and streaming over wireless links.*

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- *Wireless @ Virginia Tech is working on technologies to cater 6G use cases like autonomous networks, connectivity in 3D space and aerial drones etc.*

2.1 NSF programs

The Advanced wireless research portfolio within National Science Foundation (NSF) supports fundamental research that enable advanced wireless technologies that support faster, smarter, more responsive, and more robust wireless communications. This includes establishing and supporting experimentation on testbeds, including Platforms for Advanced Wireless Research (PAWR). There are ongoing efforts to contribute towards the Next-Generation (NextG) technologies like the few listed below.

2.1.1 Resilient and Intelligent NextG Systems (RINGS)

NSF, Office of the Under Secretary of Defense, Research & Engineering (OUSD R&E), National Institute of Standards and Technology (NIST), and multiple industry partners (Apple, Ericsson, Google, IBM, Intel, Microsoft, Nokia, Qualcomm and VMware) have partnered to develop the Resilient & Intelligent NextG Systems (RINGS) program to accelerate research in areas with significant impact on emerging NextG wireless and mobile communication, networking, sensing, and computing systems, along with global-scale services. The goal of the RINGS program is to approach the design of NextG network systems by considering resilience as the primary concern while aiming for superior performance. The program will be instrumental for enhancing the security and reliability of the NextG systems, while advancing the underlying technologies that will support stringent communication and computational performance demands that are expected of such networks over the next two decades.

Resiliency can be viewed as having several components: security, adaptability, autonomy, and reliability. While network designers have always had to balance performance and innovation with reliability and security, today's tools and techniques for network system design do not yet address the resilience of the network in a comprehensive, integrated manner, which has led to a world where factors such as security vulnerabilities, unstable updates and misconfigured systems create unpredictable behaviors. While tolerated in today's networks, these unpredictable behaviors are unacceptable in a NextG network system supporting 'essential and critical services'. In addition, multiple competing interests may be operating on the same network infrastructure, while the underlying hardware and software may be untrusted.

The proposal submitted to the RINGS program will address this challenge by addressing one or more research vectors (RV) from two groups: (A) Resilient Network Systems and (B) Enabling Technologies. Group A covers the broad range of security and resilience issues, including:

- *Resistance and/or high tolerance to attacks, failures, and service disruptions, with rapid identification of the root causes;*
- *Graceful degradation of service and rapid adaptability when resource availability is impacted by disruptive events;*
- *Resiliency in computational capabilities spread across distributed, heterogeneous, and disaggregated resources.*

The related RVs include: Full Stack Security, Network Intelligence/Adaptability, and Autonomy, and Exploratory Resiliency Components. The RV from Group B cover a broad range of enabling technologies, including: RF and Mixed Signal Circuits, Antennas and Components; Novel spectrum management technologies; Scalable device-to-edge-to-cloud continuum; and Merging digital/physical/virtual worlds.

One of the motivations for the development of the RINGS program was the Secure 5G Implementation Plan, as outlined in Activity 1.1.3 - Ensure United States Leadership in Secure 5G and Beyond Technologies. The Plan was published on January 6, 2021.

2.1.2 Spectrum Innovation Initiative (SII)

US National Science Foundation's Spectrum Innovation Initiative began advocating for a new National Center for Wireless Spectrum Research (SII-Center) that chart out a trajectory to ensure United States leadership in next generation wireless technologies, systems, and applications in science and engineering through the efficient use and sharing of the radio spectrum. The establishment of an SII-Center will have a transformational impact on wireless spectrum research by serving as a connecting point for the biggest and most challenging questions in spectrum management that the nation is facing.

2.1.3 Research Institutes/Centers

NSF AI Institute for Edge Computing Leveraging Next-generation Networks. Led by Duke University, this institute, also known as Athena, will focus on developing edge computing with groundbreaking AI functionality while keeping complexity and costs under control. Bringing together a world-class, multidisciplinary team of scientists, engineers, statisticians, legal scholars, and psychologists from seven universities, it will transform the design, operation, and service of future systems from mobile devices to networks. It is committed to educating and developing the workforce, cultivating a diverse next generation of edge computing and network leaders whose core values are driven by ethics and fairness in AI. As a nexus point for the community, this institute will spearhead collaboration and knowledge transfer, translating emerging technical capabilities to new business models and entrepreneurial opportunities. Duke's Athena partner institutions include MIT, Yale, Princeton, Wisconsin, University of Michigan and North Carolina A&T. This institute is partially funded by the Department of Homeland Security (DHS).

The NSF launched an AI research institute, also known as AI-EDGE NSF (AI Institute for Future Edge Networks and Distributed Intelligence) at Ohio University during July 2021 to improve mobile systems and networks with AI. This institute is partially funded by DHS. The institute will exploit the synergies between networking and AI to design future generations of wireless edge networks that are highly efficient, reliable, robust, and secure. New AI tools and techniques will be developed to ensure that these networks are self-healing and self-optimized. These networks will in turn be designed to unleash the power of collaboration to help solve long-standing distributed AI challenges making AI more efficient, interactive, and privacy preserving for applications in sectors such as intelligent transportation, remote healthcare, distributed robotics, and smart aerospace.

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.

OpenAirX-Labs (OAX): The Platforms for Advanced Wireless Research (PAWR) program, funded by NSF and a consortium of 35 leading wireless companies and associations, launched OAX in June 2021 as the North American home for development, testing, and integration of the OpenAirInterface (OAI) Software Alliance's open source 5G standalone software stack. As part of this effort, OAX will introduce a benchmark, end-to-end 5G implementation and provide development and test status across multiple metrics. Once initial software development and testing are complete, the open source 5G stack will be instantiated as a new software profile on PAWR wireless testbeds. It will be made available to researchers for the ongoing exploration of 5G spectrum sharing, network automation, and other advanced wireless technologies.

2.2 Next G Alliance

North America has long been a leader in driving innovative wireless solutions. In 2020, the Alliance for Telecommunications Industry Solutions (ATIS) issued a "Path to 6G" call to action to promote U.S. 6G leadership. As a result of this call to action, in October 2020, 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. With strong support from the ATIS Board of Directors, government and the ICT industry, the Next G Alliance was launched along with its founding member partners.

Although the Next G Alliance was launched as a private sector initiative, its primary objective is to influence North American government and research communities. 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 foundational 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:

- *Next G National Agenda – Brings together collective resources of private sector working with government to position North America as the global leader for Next G technologies.*
- *North American Model for Success – Creates a model built on the North American model of 6G technology developments, R&D needs, standards goals, and market readiness.*
- *6G Market Leadership – Early identification of the strategies that will lead to rapid commercialization and adoption of Next G technologies across domestic and global markets.*

Additionally, the Next G Alliance will:

- *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 Next G Alliance drives actions across a broad range of areas including policy, funding, research priorities and core technology development areas. It brings together diverse segments of the industry and leading research institutions, premised on the notion that research should be leveraged early to ultimately create a pathway to product realization and commercialization.

The alliance's structure is as follows:

- *The Full Member Group, or FMG, is comprised of senior business executives and is responsible for setting the strategy and direction and setting organizational policies.*
- *The Steering Group acts as the execution arm of the Next G alliance*

working groups. It includes a balanced leadership team representing different industry sectors. Nokia, AT&T and VMware have all brought forth leaders who drive the Next G Alliance's mission, while also ensuring the needs of vendors, operators, hyperscalers and many non-traditional players in the North American industry are addressed.

- *The MarCom Committee provides communications insight and direction to support the goals of the Next G Alliance. It will endorse and contribute to public relations, communications and marketing initiatives driven by the Next G Alliance and deliver guidance and outcome-focused direction as needed.*
- *The Policy Committee advances the goals of the Next G Alliance through engagement with U.S. and international governmental bodies and development of external alliances for purposes of supporting government policies favorable to those goals.*

In addition, working groups will be created by the Steering Group as necessary to fulfill the mission of the Next G Alliance. Virginia Tech Applied Research Corporation (VT-ARC) has been selected as the Technical Program Office (TPO) for the Next G Alliance. In this role, VT-ARC will manage and synchronize the Next G Alliance working group deliverables and engage the broader academic research community in the initiative's primary goal of establishing North American leadership in 6G.

- *The National 6G Roadmap Working Group will act as a coordination point across all working activities to establish a 6G and beyond vision. This working group is developing a National 6G Roadmap and translates the "journey" into key milestones, priorities, and needs along the path to 6G that includes technologies, research needs, application environment, sustainability goals, etc.*
- *The Technology Working Group will look across the entire landscape of air interfaces and radio systems, network/cloud fabric, edge infrastructure, x-haul needs and surrounding technologies that will lead to a core set of technology developments that drive national funding priorities.*
- *The Applications Working Group will focus on all these drivers, including how these needs translate into new KPIs. It will identify the leading vertical applications that will leverage network infrastructure in the Next G environment. The work is designed to ensure that their 6G-related application needs align with the vision set forth by the Next G Alliance.*
- *The Spectrum Working Group will explore new paradigms for spectrum access, management and sharing. It will also look at opportunities for global spectrum harmonization, technology coexistence, and greater spectrum efficiency.*
- *The Green G Working Group will aim to position North America as the global leader for environmental sustainability in future generations of wireless technology or "Green G". Its goal is to minimize the environmental impact of future generations of wireless technology.*
- *The Societal and Economic Needs Working Group will identify and characterize societal demands and economic needs to set forth a sustainable 6G business case. This group is identifying and characterizing relevant social and economic drivers (e.g., societal demands, market needs, operational necessities, and strategic imperatives) to recommend how they should influence North American 6G R&D and deployment priorities.*

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. 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, and Chinese research agencies and 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 met and 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."

Other 6G research activities from China include:

- *In Nov. 2020, China Mobile published three whitepapers: "Vision and Requirements for 2030+", "Whitepaper on Technological Trends beyond 2030" and "2030+ Network Architecture Outlook"*
- *In Nov. 2020, China launched a "world-first 6G test satellite into orbit: it will test communications for space using high-frequency terahertz spectrum."*
- *In December 2020, Ministry of Science and Technology of China (MOST) granted 15 research projects on 6G (under the framework of "national key R&D project").*
- *In March 2021, China Unicom published a whitepaper on 6G outlining mobile network evolution trends, vision on 6G application and network requirements as well as enabling technologies.*
- *In June 2021, China's IMT-2030 (6G) Promotion Group published a whitepaper on 6G vision and candidate technologies stating the 6G network would be a highly intelligent network that will integrate mobile and satellite to create ubiquitous coverage worldwide. 6G is expected to be deployed on new terahertz (300GHz-3THz) frequencies in addition to existing 5G spectrum. The white paper also noted key 6G use cases: immersive cloud based XR, holographic communication, sensory interconnection, intelligent interaction, and digital twins.*
- *Huawei sets to launch test satellites for 6G technology verification in July 2021.*

3.2 Japan 6G Efforts

MIC (Ministry of Internal Affairs and Communications) set up the 'Beyond 5G Promotion Panel' in January 2020 to discuss Beyond 5G (B5G) strategy and policy to re-vitalize the Japanese ICT industry in terms of international competitiveness taking into consideration the expectations for the society in 2030s and required technology components. The panel consisted of representatives from the private sector and academia. They published "Beyond 5G Promoting Strategy" in June 2020 including specific measures and roadmap to promote B5G in Japan.

According to the above roadmap, the Beyond 5G Promotion Consortium and Beyond 5G New Business Strategy Center were established in December 2020. The former is the core organization to promote the strategy among industry, academia, and government, accelerating various initiatives, and promoting international collaboration. The Planning & Strategy Committee and International Committee have been set up inside the consortium for execution of actual activities. The New Business Strategy Center is meant to accelerate securing intellectual properties by the Japanese players and promote global standardization strategically.

In line with the Japanese Beyond 5G Promotion Strategy above and the concept of Society 5.0 that the Japanese government is promoting, several companies and research institutes have been issuing B5G/6G whitepapers including NTT DOCOMO, KDDI, NEC and NICT (National Institute of Information and Communications Technology). While, NTT has been promoting its vision of IOWN (Innovative Optical and Wireless Network) which, they claim, includes 6G in its scope. In addition, the Whitepaper Sub-committee under Planning and Strategy Committee of Beyond 5G Promotion Consortium is developing its own whitepaper to present Japanese views on 6G/B5G including Japan-specific requirements and objectives, for international discussions including contributions to ITU-R.

In Jan 2021, Japanese government announced it will earmark $482 million for 6G R&D.

In April 2021, U.S. President Joe Biden and Japanese Prime Minister Yoshihide Suga have agreed to jointly invest $4.5 billion for the development of next-generation communication known as 6G, or "beyond 5G.". MIC secured about $500 million for B5G R&D funding (US$300 million) and B5G testbed ($200 million) as part of FY2020 budget for the coming three years. In addition, MIC has secured about $600 million for FY2021 for B5G R&D and METI (Ministry of Economy, Trade, and Industry) has secured about $800 million for Post 5G as part of the FY2020 budget.

3.3 European 6G Efforts

Europe has also moved forward with variety of different 6G initiatives spanning government and academia. These activities are at the Europe-wide, regional, and national level.

3.3.1 Europe-wide Level Activities

The following 6G-related activities are occurring on a Europe-wide level.

3.3.1.1 Horizon2020 - 5G Public Private Partnership

Within the overall eight-year European research framework Horizon2020, a public private partnership has been set up to perform research and innovation in cellular communications. Within the 5GPPP, there are also a specific set of projects investigating 6G referred to as ICT-52 projects. This set of nine projects cover many of the key technology areas foreseen for 6G. The projects include one flagship project named HEXA-X. These projects started at the beginning of 2021.

3.3.1.1.1 Hexa-X

The Hexa-X project was officially launched in January 2021. It is a European Union sponsored project within the ICT-52 framework. The project aims to shape the European vision and foundation for a 6G systems targeting 2030 and beyond and to carry out exploratory research on key technologies that can enable this vision. The project, which will run until mid-2023, brings together key industry players and major service providers, together with major European research institutes.

3.3.1.1.2 REINDEER

The REINDEER (Resilient interactive applications through hyper diversity in energy efficient Radio Weaves) project was launched in January 2021 and will run until mid-2024. It is a European-Union funded project with the goal of establishing foundations for next-generation ("6G") distributed multi-antenna technology. The project includes infrastructure providers, service providers, semiconductor suppliers, and academic institutions.

3.3.1.1.3 Horizon Europe - Smart Networks and Services

The next 8-year European research framework will be called Horizon Europe. Within this framework a new partnership called Smart Networks and Services will be launched to invest in 6G research and innovation. The partnership will be jointly run by the European commission and European industry, which is represented by the 5G Infrastructure Association (5GIA).

The intension is that this partnership will start in Q4 2021 and invest somewhere around 900 million Euros in research and innovation actions. This 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.

3.3.2 National Level Activities

The following 6G-related activities are occurring on a national level in Europe.

3.3.2.1 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 and two additional company co-creators. In June 2019 ETRI (Korea) signed an MOU with the University of Oulu.

All 12 6G Whitepapers were published by April 2021.

3.4 Korea Efforts

The government of Korea's strategy for 6G consists of preemptive development of next-generation technologies, securing standard and high value-added patents, and laying R&D and industry foundations. The government of Korea reportedly expects to invest a total of KRW 200 billion (US$169 million) between 2021 and 2026 period to secure basic 6G technology.

The Korean government expects to launch a 6G pilot project in 2026 and it has selected five major areas for the pilot project as digital healthcare, immersive content, self-driving cars, smart cities, and smart factories.

In March 2021 Korean tech giant LG partnered with U.S.-based test and measurement firm Keysight Technologies and the Korea Advanced Institute of Science & Technology (KAIST), with the aim of carrying out research on future 6G technologies.

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. 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.

At the 6G Symposium Spring 2021 event, Dr. Li Fung Chang, Chief Architect, 5G Program Office at the Industrial Technology Research Institute (ITRI) of Taiwan presented their B5G activities and the exploratory work they have done for 6G. The enhanced user experience through 6G include unmanned vehicle, smart health, interactive remote robotics, 3D holographic, ubiquitous networks, AIoT (Artificial Intelligence of Things), ultra positioning and enhanced public safety. Dr. Chang also discussed opportunities for the industry to explore network components from the core, RAN, end device to IC/modules/components to accelerate the evolution towards 6G.

Chunghwa Telecom Laboratories in Taiwan has also initiated a R&D project of low earth orbit satellites.

3.6 India Efforts

In India, TSDSI is contributing towards IMT 2030 work and submitted to ITU in June of 2021 their 6G Vision. The basis of their submission is the following;

TSDSI's strategy focuses on four main areas:

- *Technologies that aid development of a Ubiquitous Intelligent Mobile Connected Society*
- *Technologies to Bridge the Digital Divide*
- *Support technologies that can Personalize/localize services*
- *Support technologies that can mimic real world data ownerships and hierarchies*

TSDSI has focus on their strategy on two areas for 6G:

- *Steer research in India to serve the above goals*
- *Continue engagement with global standards bodies for harmonization of efforts including ITU WP 5G.*

Additionally, a study on use cases, requirements, and technologies towards 6G is ongoing in TSDSI.

4. Use cases

This section, as well as an area of the appendix section, discusses a variety of possible new and/or extended use cases that are currently being discussed across the industry.

Some of these use cases can be realized by means of the continuous ongoing evolution of current 5G technology. Other use cases most likely require a more radical step, i.e., a "new generation" of wireless technology, for their ultimate realization. While such applications have started seeing the light of day throughout 5G systems in their nascent stage, current 5G technology still falls short in delivering the extreme requirements needed to deliver evolutionary use-cases of such applications.

Hence, we overview these potential use cases from a customer's point-of-view and do not restrict our comprehensive elaboration to any implementation. Furthermore, as the consumer and industrial needs continue to mature, various peculiarities regarding these use cases remain subject to change.

4.1 Multi-sensory Telepresence and Immersion

Extended Reality (XR) services have started to emerge in current 5G systems. XR services encompass a continuum of experiences from Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). On the "virtual" end of the spectrum, the goal of VR system is to give users a sense of absolute presence and immersion by generating sensorimotor and cognitive activity in an artificially produced environment. Additional VR, AR, and XR use cases can be found in Appendix: UC 1 Augmented Reality/Virtual Reality/Mixed Reality.

When such systems are deployed on wireless networks, their high quality and uninterrupted visual components require extremely high wireless data rates. Meanwhile, their highly sensitive component requires an extremely low latency and high wireless reliability. On the "reality" end of the spectrum, the goal of AR system is to overlay reality with virtual objects. Furthermore, AR shares rate-latency-reliability requirements with VR but is less stringent on the haptic component since the user will not need to be "immersed" in its artificial environment.

XR services require a high instantaneous data rate in addition to a high peak data rate and can cover a wide range of applications such as remote medicine & telesurgery, human technicians for factory floor, and immersive gaming. While current 5G technology can deliver data rates of advanced XR, such as full-view 12K video, it falls short in delivering ultimate XR experiences that necessitate a full-view 24K video. Moreover, incorporating the five senses in the XR experience necessitates data rates higher than the ones reported by ultimate XR. Incorporating these five senses also requires more stringent end-to-end latency, jitter, and synchronization.

Co-existing AR and VR capabilities in the same device leads to the concept of MR, which is a sort of mid-point in the virtual-real spectrum. With the evolution of 3D imaging, MR is evolving to create the highly sought-after holographic teleportation concept. Subsequently, such services have even more stringent requirements on the wireless network since holographic flows require very tight synchronization of the five senses. Additionally, while the visual component is of utmost importance in some applications, some services require a focus on the tactile and haptic component.

Such services include tactile internet and wireless brain-computer interactions (BCI). For example, BCI applications allow humans to control prosthetic limbs or neighboring computing devices using brain implants. Furthermore, as such services mature, they will not be limited to healthcare applications but will also allow individuals to control their environments through gestures and remotely communicate with others using haptic messages.

4.2 Industry 4.0 and Digital Twins

Cyber-physical systems are highly integrated systems of physical components that involve sensors, actuators, and various other devices that provide ubiquitous computation and communication. Such systems end goal is to either mimic the human behavior or to make decisions in environments that require human interactions. Examples include self-driving cars, autonomous robots, social robots, etc.

In terms of cyber physical systems, we are currently in the Fourth Industrial Revolution. These are industrial automation systems that, through their networking and access to the cyber world, enable a wide range of innovative functions, significantly altering our daily lives. In some cases, Industry 4.0 in manufacturing has also been referred to as a “smart factory” or a “lights-out factory,” an industrial environment that can run semi- or fully autonomously. It focuses on the ability to collect information, share information, and use that information to make better decisions (in a decentralized way) and be more productive.

Furthermore, to provide current cyber-physical systems with a full autonomy and an end-to-end digitization, the concept of digital twins has recently emerged as a means for creating a model for complex physical assets, thus scaling up the digitization of complex industrial structures and empowering them with full autonomy. In particular, 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. In fact, the physical counterpart can only be fully mimicked by enabling a real-time synchronization between the cyberspace and physical spaces.

Moreover, given the large number of sensors continuously aggregating data to update the virtual model, the connection needs to be delivered at high data rates as well as stricter bi-directional reliability requirements across thousands of devices with near-zero response times. Hence, one needs to investigate novel wireless capabilities beyond 5G that enable delivering bi-directional reliability for such a large number of devices and real-time data transfer translated by very low delay jitter. Furthermore, digital twins are used to make predictions on the evolutionary dynamics and future states of large-scale systems, as well as to control them in real time. As a result, failures can be predicted, the system can be optimized to design novel features, and the decision-making process can be guided. As a result, offloading data from physical models is extremely error-prone, particularly during the initialization of physical models. More use case information is available in Appendix: UC 5 Digital Twins.

Digital Twins can be useful in many IoT use cases where data is collected from sensors. For example, health monitoring and reporting related use cases (see Appendix UC 8 Medical/Health Vertical) can benefit from sensor data that measure biometrics such as temperature, pulse rate, glucose levels, blood pressure, etc. that feed into digital twins representing medical/disease diagnostic models.

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. Smart cities sensors can be integrated into such things as parking spots, trash, air quality, and utility meters.

4.3 Verticals

Current 5G systems have already caught the interest of many specialized vertical industry sectors. This trend will continue with next generation systems supporting even more challenging verticals across areas such as agriculture, automotive, healthcare, smart factories, smart cities, education, media and entertainment. A few examples of vertical use cases are examined in this paper.

Smart agriculture and livestock are cyber-physical systems that use a massive amount of simple IoT sensors devices spread out over large areas like cities, farms, and roadways. 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 give farmers the ability to foresee production output, while allowing farmers to plan for better product distribution.

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. “Precision livestock” enables farmers to monitor the needs of livestock herds on an individual animal basis. Note that, current 5G systems can potentially fulfill precision farming’s wireless requirements. Nevertheless, achieving the extremely power-efficient and long-range communication capabilities, along with the distributed ML capabilities are envisioned to be comprehensively fulfilled in next generation wireless systems. See Appendix: UC 6 Smart Agriculture and Livestock.

The transportation vertical includes autonomous vehicles and swarm systems. The current V2X (Vehicle-to-Everything) communication technology, including Vehicle-to-Network (V2N), Vehicle-to-Infrastructure (V2I), Vehicle-to-Vehicle (V2V), Vehicle-to-Pedestrian (V2P), will be enhanced in next generation systems.

There will be improved efficiency of transportation systems (car platooning, speed harmonization, smart intersections), advanced driver-assistant systems (see-through, high definition sensor sharing, real-time high definition maps), improved transportation safety (left turn assist, vulnerable road user discovery), improved autonomous driving (remote driving assistant for autonomous vehicles, cooperative maneuver of autonomous vehicles, cooperative perception, cooperative safety), and advances in Intelligent Transportation Systems (faster emergency response and road operators, smart highways with autonomous driving lanes, dynamic traffic flow management). See Appendix: UC 7 Transportation Vertical.

Medical/Health vertical's 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. A multiplicity of biosensors for monitoring health conditions – pulse rate, blood pressure, EKG, neural scan, blood glucose, etc. – are potential opportunities for next generation connectivity. See Appendix: UC 8 Medical/Health Vertical.

Verticals supporting first responder and emergency services requires a reliable (in terms of availability, reliability, and resiliency), ubiquitous, network agnostic communication framework providing voice, data, and video, and other emerging communication technologies. Building on 5G-based networks, next generation first responder networks 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. See Appendix: UC 9 First Responder/Emergency Services.

Verticals for governments often seek to deploy networks with national security requirements that provide 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. Some of these are outlined in the U.S. Department of Defense (DoD) "5G to NextG" strategy. See Appendix: UC 10 Government/National Security.

5. Technology Requirements and Network Evolution

This section collects the technical requirements and capabilities needed to deliver the use cases described in Section 4, as these requirements will be addressed by new technological advancements, we will also summarize how such advancements will need to align and collaborate to solve the business problems for wireless networks as a whole. Sub section 5.1.9 provides a summary table that maps technology requirements to use cases.

The final subchapter discusses the overall needs for the future 6G wireless networks, which are not going to evolve simply due to advancements in technology but to address tangible and business-oriented use cases, as well as adapt to the changing landscape of IT world and the environmental impact of the industrial world.

More specific approaches and solutions are pursued later in Section 6.

5.1 Technology requirements

The technology requirements are service level requirements and capabilities, which are intended to be independent of any implementation approach. 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.

5.1.1 Very High Data rates

While 5G users can expect speeds in the hundreds of Mbps (minimum end user speeds 100 Mbps/50 Mbps), this will be insufficient for some next generation use cases. Estimates for high fidelity holographic immersive services range from 0.5 – 1.0 Tbps. digital twins, tactile & haptic communications and related cyber-physical systems require data rates more than 100Gbps for non-holographic immersion and, in addition, require a fast uplink due to the need to send information from the device back to the cloud.

5.1.2 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).

5.1.3 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 1-10^{-5}. However, this requirement will be insufficient for next generation use cases such as telesurgery other health related services, industrial remote control/ digital twins modeling applications, transportation vertical, and national security/government services. These demanding next generation services require reliability and redundancy that approach “seven 9’s” availability (99.99999%).

5.1.4 High Density of Endpoints

The proliferation of vast numbers of endpoint devices in an area hampers the ability of the radio access network (RAN) to scale connectivity to all these devices. While the aggregate traffic demands of these mIoT devices are manageable, it is challenging to efficiently manage the signaling and operational overhead.

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. But emerging use cases will demand device density to increase tenfold up to 10 million devices per square kilometer.

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.

5.1.5 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.

5.1.6 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.

5.1.7 Precise Location Tracking

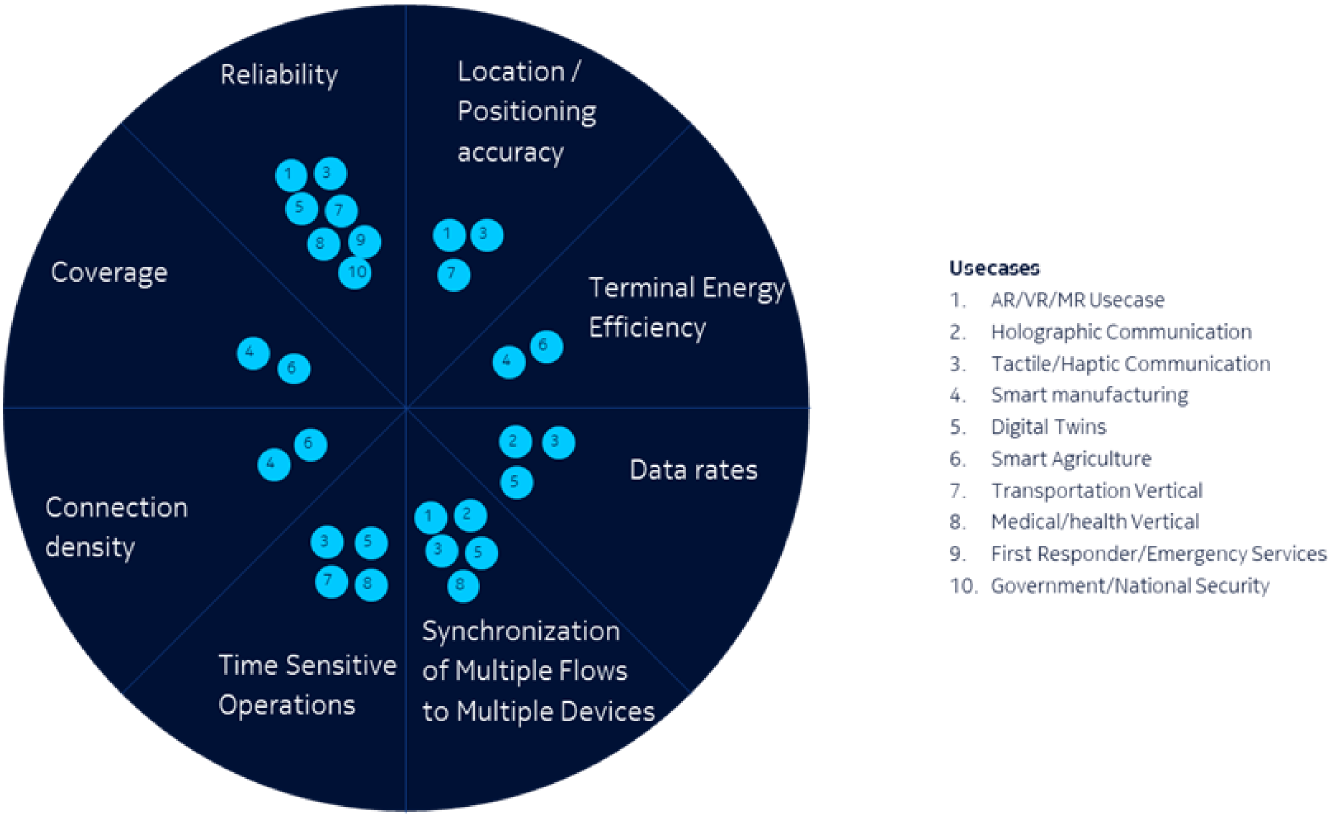
For advanced 5G and beyond use cases, the role of “location services” grows into the precise location tracking of objects in the vicinity of the user as well as tracking the device location. For the device, this includes real time and precise location and orientation tracking of headsets, glasses, or 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.

5.1.8 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, or even never needing to be charged (e.g., absorbing energy from its environment). This could allow them to have an unattended operational lifespan of more than ten years. 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.

There will be a need for devices to be supported unattended across more than one generation (e.g., 10 years). Deployed IoT devices with a very long lifespan may be deeply embedded into national infrastructure (e.g., roads, bridges, buildings, cars etc.). It may, for example, require them to be remotely field upgradable by making them forward compatible to the next generation of network protocols especially in the non-access stratum. Additional considerations would also be required around long-term spectrum planning and spectrum harnessing for next generation of

Figure 1: Use Cases to Tech Requirements mapping



networks for such long-life devices that may continue to operate in some frequency bands across multiple generations.

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.

5.2 Network Evolution

The technology requirements will push for a mobile network evolution with more advanced capabilities, where new architectural characteristics or completely new architectures will be needed to satisfy and enable them.

To support the requirements for use cases, the technology advancements that seem to have acquired significant 'critical mass' in the industry to be considered in the network evolution roadmap towards 6G can be grouped as following:

- *Hardware Acceleration and possibly different types of Metamaterials*
- *Widespread use of AI/ML*
- *Higher reliance on open source*
- *Continued cloudification and Architectural enhancements*
- *Internet and IP network evolution and convergence of Internet, telecom, and media*

There will be obvious synergies between such groups, as technical solutions will be developed for enabling various use cases. One of the examples maybe worth pointing is the trend of introducing ML and even AI in all network components – from RAN layers all the way to operation – which could benefit from an open source development environment as well as by the trend in cloudification that will add the efficiency and delivery speed of hyperscalers to the mix.

From the perspective of network operators, as they will not only provide connectivity but also services, performance insights, exposed interfaces with network computation capabilities for third parties while also ensuring their network development fits in their business model and environmental constraints, these technological advancements would ultimately need to evolve and work together to achieve the following characteristics:

- *Extreme performance*
- *Trustworthy*
- *Intelligent and Cognitive*
- *Capable of Rapid and flexible deployment*
- *Sustainability*

5.2.1 Extreme Performance

Future wireless networks will be built to provide extreme performance everywhere to existing and novel use cases. Some of the streams of development working to achieve such endeavor are highlighted below:

- *Wireless networks will be migrating towards versatile systems that have joint sensing and communication capabilities with spectrum use expanding towards higher frequency bands. Developments in mmWave and terahertz spectrum sharing together with communication and sensing co-design are some of the enablers in this direction. See chapters 6.5 and 6.7 for more details.*

- *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 will be a necessary component of the pervasive coverage envisioned for 6G to realize truly global overage for future wireless connectivity.*
- *The 6G networks are envisioned to support trillions of embedded devices and provide trustworthy connections that are available all the time. This also calls for ``zero-energy" devices – devices that consume very small battery life or no need to charge battery by harvesting ambient energy for operation (vibration, heat, light, etc.). 6G Network may need to employ lightweight communication protocols to support ``zero-energy" devices.*
- *As new packet fronthaul and wireless transport technologies get developed, such as relay and mesh networking, free-space optics and further integrated access and backhaul, more dense deployment with extreme capacity becomes feasible. See chapter 6.11 for more details.*
- *New architectural approaches that innovate on existing concepts and technologies to facilitate seamless connectivity and management, such as subnetworks and cell-free ultra-massive MIMO clusters. See chapter 6.4 and 6.9 for more details.*

5.2.2 Trusted network

The four important building blocks for trustworthy systems are security assurance and defense, service availability, secure identities and protocols, and confidential computing solutions. AI is expected to have a major impact on future technology evolution as well as security and is expected to help in all the four areas mentioned above.

See chapter 6.13 for more discussion on security in future networks.

5.2.3 Intelligent and cognitive network

Future wireless networks will become more intelligent and cognitive to deliver the needed capacity without raising the cost and the complexity significantly.

Evolution towards cognitive networks can occur – not limited to – the following directions:

- *in optimizations that are difficult to achieve with basic algorithms, where AI/ML can support (See Chapter 6.2 "AI/ML in the RAN" for further discussion on AI/ML application in the lower RAN protocol stacks), and*
- *in evolving the operations systems to handle most of today's system management tasks autonomously, where AI/Machine Reasoning (MR) can play a vital role. Some of the areas in network operation and management that can benefit are:*
  - » *Data-driven operation*
  - » *Distributed Intelligence: Smart algorithms guide all the aspects of network operations and procedures using the right mixture of local, distributed, and centralized AI. See chapter 6.1 for more in-depth discussion on distributed intelligence.*
  - » *Intent-based management: Control the system operations with high-level intents to state operational goals, where detailed configurations are performed by the management system.*

Explainable & trustworthy AI: Novel ML and AI frameworks beyond black box configurations are needed to provide trusted, interpretable, and explainable decision-making process. In addition, E2E network functions become more natively intelligent, in other words, applications and networks become mutually aware of each other's need and current situation, so they can collaborate to achieve high performance connectivity.

5.2.4 Rapid deployment and flexible network

Wireless networks will become more adaptive and capable of rapid deployment and quick flexible addition of new services. This is reflected in three areas:

- *Flexible and dynamic networks with integration of new types of access nodes, versatile AI-powered programmable transport for cost effective densification, and the ability to address needs from enterprises and various verticals.*
- *Network architectures optimized for cloudification, mainly based on a common cloud platform and IT tools (such as orchestration and management), see chapters 6.7 and 6.8 for more discussion on network cloudification.*
- *Programmable devices and network elements allow the development and deployment of new features (DevOps).*

5.2.5 Sustainability

Sustainability within the context of future wireless systems has two dimensions:

- *Sustainability enabled by the wireless system, also referred to as "6G for sustainability"*
- *Sustainability within the wireless system, also referred to as "sustainable 6G"*

With regards to the former ("6G for sustainability"), creating a more sustainable society will be a key challenge for the future and the availability of state-of-the-art wireless-communication systems have the potential to be a key component in the realization of this.

Some examples include:

- *The availability of advanced wireless connectivity can enable more efficient utilization of limited resources such as energy, water, and arable land. This includes, for example, the possibility for ultra-reliable connectivity for intelligent transport systems and connected* *embedded ultra-low-cost devices/sensors for smart cities, within agriculture, etc.*

- *The availability of wireless connectivity with truly global coverage will enable new opportunities for, for example, education and personal health services for everyone everywhere.*

At the same time, the design of future wireless systems must be such that the systems themselves can be deployed and operate in a sustainable way (“sustainable 6G”) by, for example, limiting the energy consumption and, as a consequence, the CO2 footprint of system deployment and operation.

6. Technology Enablers and Trends

This section provides examples of concrete technical approaches or solutions that satisfy the technology requirements collected in Section 5.1 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.

6.1 AI/ML at the Network Edge

Artificial intelligence is turning out to be an important resource that enables more powerful services across several use case categories. At the same time, the necessity of artificial intelligence at the edge of the network is also becoming clearer.

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.

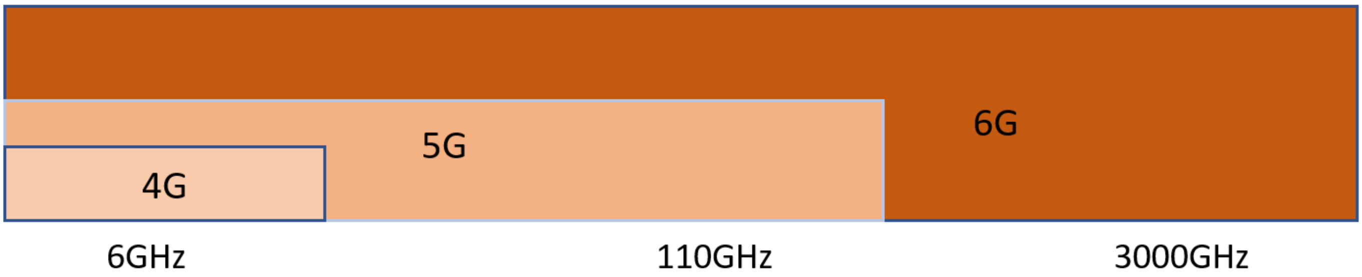
Training AI models usually require time spent to collect the data for machine learning models, training these models, and defining actions based on the learned models to be returned to the application. Some use case categories such as mission critical applications demand accurate responses within a very 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.

6.2 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

Figure 2: Spectrum Usage for Different Generations



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.

6.3 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.

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 (see Figure 2).

The capability 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.

The short wavelengths make for accurate sensing, imaging, spectroscopy 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. Extremely low power consumption radios become possible by closely locating mmWave and THz transmitter and antenna components.

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. The challenges span the mmWave/THz air interface and the transport and processing of signals at terabit/sec speeds.

Table 1 captures the various air interface challenges and the proposed beyond-leading-edge technical capabilities to overcome these challenges.

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.

Table 1: Above 110 GHz:Greenfield Air Interface Challenges & Beyond-leading-edge technical capabilities

Greenfield Air Interface Challenges	Beyond-leading-edge technical capability
Sever path-loss and atmospheric absorbption	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 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.

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.

The current set of beam management techniques based on hierarchical beamforming 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 Power Amplifiers (PA) and Low Noise Amplifiers (LNA) 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. 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. 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, or sleepy networks) and sharing learned experiences with other nodes via federated learning mechanisms.

6.4 Communications and sensing co-design

We foresee the concept of versatile wireless networks, such as co-designing networks for both communication and sensing purposes would be one of the key technology enablers beyond 5G systems. This concept will emerge in the next generation wireless systems due to two main factors:

- *The use of mmWave and THz spectrum enables wireless networks to benefit from abundant bandwidth, and thus enables an improved resolution of sensing compared to sub-6 GHz and low band spectrum. Also, such frequency bands have a small antenna footprint, and thus their directionality improves the accuracy of sensing, this is particularly important for mapping and localization.*
- *The novel 6G use cases such as the digital twins and multi-sensory XR necessitate a communication and a sensing input to provide a seamless experience. For instance, systems with large bandwidth in sub-THz bands with associated small cells configurations will present special opportunities in this regard for indoor mapping and sensing in locations, such as factories.*

Novel 6G use cases will pave the way for Radio Detection and Ranging System (RADAR) as 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, such as a human or a car, and process the received signal to derive properties such as distance, posture, velocity, and/or size of targets within range of the radio base station.

Moreover, choosing the carrier frequency used for sensing will be determined by the accuracy-range tradeoff. High frequency bands, owing to their bandwidth and high directionality, enable high-resolution measurement of the environment, and accurate detection and recognition of 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. Thus, such frequency bands are useful for applications that necessitate a high-resolution sensing measurement like localizing a UE or target in the cm and degree range in mainly indoor applications. Nonetheless, such frequency bands face challenges in offering sensing input for longer ranges and outdoor use cases such as autonomous vehicles, due to high attenuation effects like rain and foliage and propagation losses.

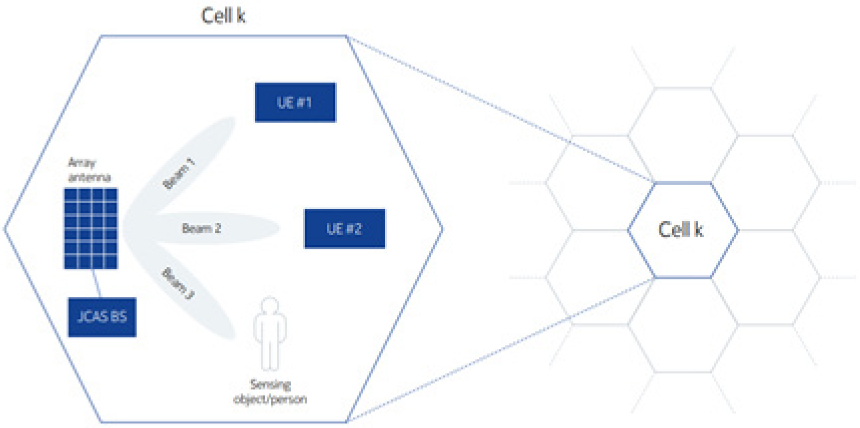
Furthermore, the synergy between mmWave/THz frequency bands and frequency selectivity allows us to determine relative electromagnetic absorption rates. Thus, this is expected to lead to significant advances in wireless sensing technology. For example, this sensing functionality allows analyzing gas compositions which is particularly important for environmental sensors that monitor air pollution.

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.

A basic joint communication and sensing (JCAS) system with beamforming antennas, UE for data transmission and sensing objects and persons is depicted in figure 3.

One way to enable joint communication and short-range sensing is to use the standardized downlink signal as the excitation signal, for example the orthogonal frequency-division multiplexing (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”, for instance, without having to assign network capacity specifically for this purpose. However, choice of waveform

Figure 3: Basic joint communication and sensing (JCAS) system



deserves diligent attention and a multiplex of different waveform candidates such as frequency-modulated continuous wave (FMCW) and OFDM may be a good option to optimize parameters such as Peak-to-Average-Power-Ratio (PAPR), data throughput and communication protocol flexibility. Also, methods for reducing sensing overhead need to be analyzed more.

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.

6.5 Spectrum sharing, new spectrum usage and co-existence

The very high frequency bands of 6G technology must co-exist with the technology in lower frequency bands. As discussed in Section 6.3, 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 are 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.

6.6 Cell free, ultra-massive MIMO

Conventional cellular networks (namely 4G & 5G) architecture is based upon a network-centric approach where each user is connected to a cell, and a notable side effect of it is inter-cell interference at the cell edge, which causes degradation in signal quality. As such, the users on the cell edge are usually served with a low quality of service due to comparatively long distance from base station and unfavorable channel conditions. The increased requirements of higher data rates demand low inter cell interference, specifically at cell edge where it is inevitable due to multi-server environment.

To address such cell edge problems at low band sites, recent advances in active antenna array technologies like full dimension (FD) MIMO introduced in LTE Rel 13, were designed to support massive antennas at the base station in a computationally efficient way. However, it can be difficult to utilize massive MIMO with low band spectrum due to half wavelength distancing requirement between antennas.

As efforts to address these issues continue, concepts relating to D-FD-MIMO (Distributed Full Dimension MIMO) include distributed massive MIMO, Coordinated Multi-Point (CoMP) “a.k.a. network MIMO” and distributed antenna systems (DAS). Distributed massive MIMO treats the entire network as one cell, featuring an enormous number of access points distributed over a large area, jointly serving all the users. CoMP relies on the coordination among a few transmission points from the same or different sites to enhance User Equipment (UE) experience at the cell edge. DAS is initially proposed to improve coverage in an indoor cellular communication system and is sometimes adopted in outdoor scenarios as well.

As a summary, the following solutions have been explored in current research:

- *Inter-cell interference cancelation (ICIC) introduced in LTE.*
- *Coordinated Multi-Point transmission and reception (CoMP) both in downlink & uplink.*
- *Joint Transmission (JT)*
- *Multi-input multi-output (MIMO) techniques can use spatial beamforming to increase signal-to-interference-and-noise ratio (SINR) for cell-edge users.*
- *Coordinated Beamforming.*

Cell Free Massive MIMO also termed as Distributed-Full Dimension-MIMO/ Modular Massive MIMO is an evolution of Full Dimension-MIMO. A D-FD-MIMO network assumes a cellular structure, where a cell is served by one base

Figure 4: Inter-cell interference effects

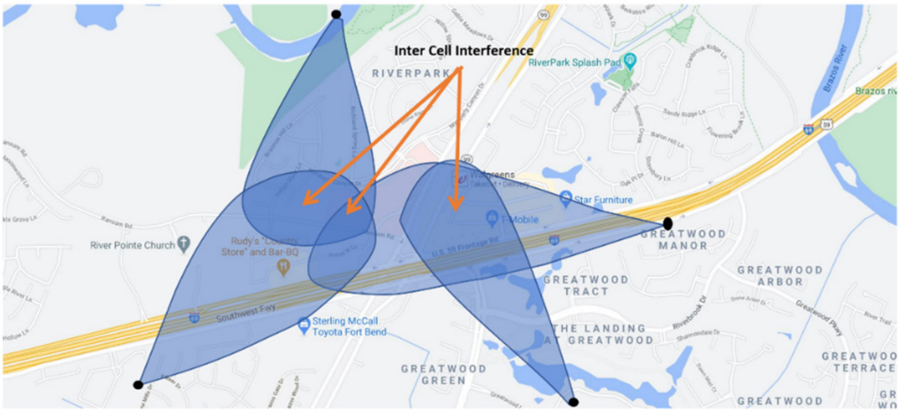
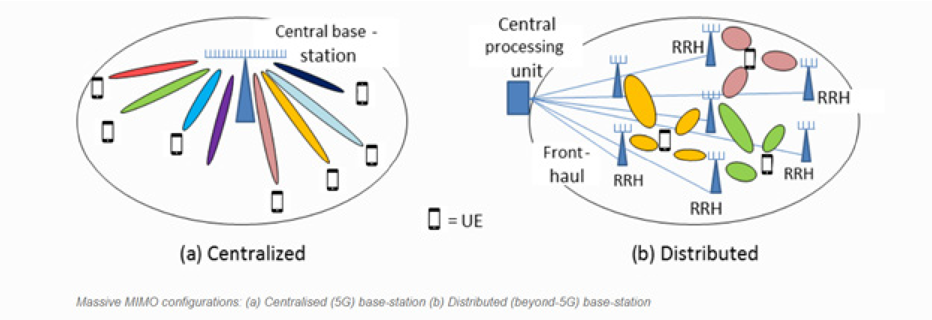


Figure 5: Massive MIMO configuration (a) Centralized (5G) Base Station (b) Distributed (beyond-5G) base-station



Massive MIMO configurations: (a) Centralised (5G) base-station (b) Distributed (beyond-5G) base-station

station (BS) and each BS relates to a large number of antenna elements, of which individual elements are spatially distributed in the cell. One or more antenna elements are equipped with a digital port, and the signals transmitted and received from all the antenna elements within one cell are jointly processed to perform high order MU-MIMO operation. The goals are to ensure UE will have one or more short, distanced servers but also to benefit from a larger spacing between multiple servers.

The perspective changes from network-centric to user-centric connectivity where the cell boundary problem is exploited in terms of dynamic cooperation clustering of multiple access points that serves a small group of users.

In the same realm, recent studies of Modular Massive MIMO (mmMIMO) have been showing significant improvements in the low band domain. mmMIMO can be viewed as an evolution of the structured D-MIMO with various predefined basic antenna modules and flexible combinations of them to build a single system. Group of horizontal and vertical antennas can be exploited to steer beams in two dimensions.

It was observed that the average UE throughput is improved more than twice as the number of antenna modules increases. It was also seen that the cell-edge UE throughput is even more significantly improved. This is not only because of the improved overall system performance but also because the distributed antennas can be electrically, or even mechanically in practice, steered to shed beams towards different directions, resulting in a better coverage of the cell area.

As the work on this continues, some of the main challenges worth mentioning are as follows:

- *Implementation of cell-free approach in different frequency bands*
- *Time synchronization*
- *Coordination between base stations (not APs)*
- *Architectural shift from flat to hierarchical (which can provide more coordination between nodes)*
- *Delay spread requirement for transmitting signal from spatially separated nodes needs to be explored on the macro cell level*
- *Channel state information reporting and processing is another bottle neck*

Ultimately the cell-free architecture can be successful in addressing the cell edge problems, and its approach of increased densification of cellular coverage (extraterrestrial/macro/micro/pico-cells) can be utilized to increase channel quality.

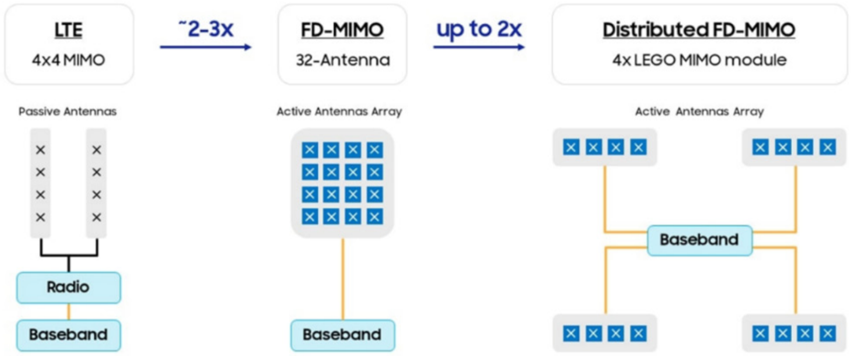
6.7 Cloud Native, Service based Mobile network convergence

In the 5G era, the transition of 5G core network 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.

The trend in communication networks towards “software-ization” and disaggregation of network elements into more granular microservices that can be spun up on the fly and operate relatively independently will continue. In 5G this was limited to the core but already we see it now expanding into RAN where in O-RAN, RAN elements are being disaggregated. The next step in this RAN transformation would be service based interaction amongst these disaggregated RAN elements as well as with the core network. These changes would result in blurring the line between RAN and the core network and allow for a much more flexible and on demand deployment of required RAN and core collocated network functionalities at a much more distributed and granular level.

Beyond 5G networks are likely to be extreme-edge or edge centric and data flow-based across the network. Network functions and other

Figure 6: comparison of LTE, FD-MIMO and D-FD-MIMO deployment scenarios



workloads would be dynamically scheduled in a hierarchy of data centers across the network topology. 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.

One of the most important dimensions of cloud native architectures is how they are delivered and orchestrated: the transition to the DevOps 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. However, as the use cases continue to grow in complexity and criticality, new forms of integrated computing fabric will be needed to complement today's edge solutions. This integrated computing will allow a powerful unified form of computing by closely linking computing, processing, network nodes and connections leading to a network compute fabric.

There are multiple technology trends in the compute and storage space, many of them poised to have a huge impact on how we develop telecom software systems. Limits to Moore's law will start impacting compute and memory paradigms. New demanding use cases will require CPU-assist technologies such as accelerators. This will give rise to domain specific accelerators, optimized for a certain class of applications. On the memory front, advancements in technologies like Non-Volatile Memory over fabric (NVMeOF) will be crucial to meet strict latency requirements. The latency demands of the new use cases combined with increasing disparity of CPU speeds vs. memory access speeds will push compute units to be embedded either inside the memory or storage fabrics, opening up for near-memory computing (NMC) or computational storage approaches.

While some of these trends can be handled in the lower levels of software (kernel, infrastructure libraries etc. thereby masking its impact from the applications), others may require a complete rethink, including new hardware abstraction layers, new programming models and new ways of dealing with system resiliency. The current CaaS and PaaS solutions and tools and the overall Cloud Native paradigm will evolve and extend to allow these transformations and provide a new level of platform agnostic cloud native layer for the next G applications.

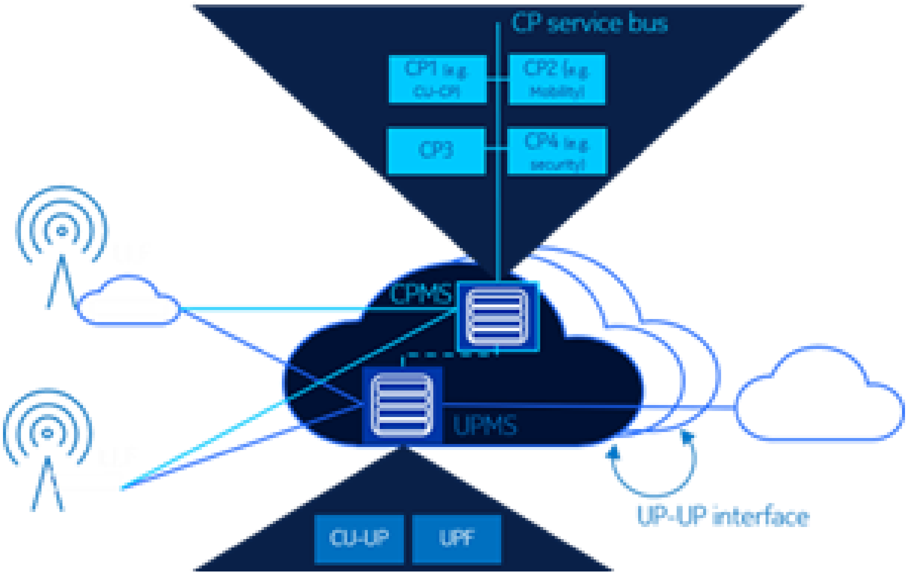
Next G networks will become increasingly an integral part of the society, and this will bring about new requirements of higher availability and resilience. Industry transformation and cyber-physical systems both demand a universal network compute fabric to handle massive amounts of data, provide extremely low latency, and ease programmability and operation within a continuum of execution environments, from devices to the network edge to local and central data centers. The network compute fabric will unify the telco-IT ecosystem, and execution environment, allowing harmonized data infrastructure and application management for the next G networks.

Leveraging such network compute fabric, future deployments will become less node-centric, and both RAN and Core networks (CN) will have more common infrastructure platforms. This will make it important to revisit some architecture assumptions behind today's functional separation between RAN and CN.

A key part of this journey will be to choose smartly when it comes to the right set of RAN and CN functions and interfaces to provide the best performance, use cases, and deployment versatility while keeping development efforts and network operations manageable.

There are additional opportunities to harmonize the RAN and core functions to create a simpler network. We envision that the next G network

Figure 7: RAN Core Convergence



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.

6.8 Communications & Compute Convergence

The coming together of Internet, telecom, media, and information technologies will result in a world-wide system of interconnected components acting as a global nerve system. This system integrates communication, computation and content allowing cross-domain innovation. 6G is expected to bring all physical things into the realm of compute and acts as a connector and real-time controller of cyber-physical systems. It will host computing and storage, tightly intertwined with communication.

Some of the trends and external forces that have been happening and continue to expand to shape the future network evolution and the adoption and proliferation of network compute fabric (NCF) are:

- *Gap between telco and IT ecosystems decreases*
- *Increased use of IT technology in telco and partnerships*
- *Emergence of millions of sub-networks (see chapter 6.10 "Sub-networks" for more discussion)*
- *Transformation towards cloud-based solutions in many domains, e.g., telco, evolution of Industry 4.0, and XR*
- *Special hardware accelerators to enhance the performance for a given energy envelope*
- *Increased focus on data and its value; data-driven principles impact most aspects of systems*
- *Increased use of open source*
- *Compute off-loading and heterogeneity, deterministic E2E performance*

The Network Compute Fabric (NCF) includes the set of capabilities which would transform the network from pure connectivity to an innovation platform. The network and 3rd party applications utilize the same fabric to target new businesses.

Initial steps of the NCF are already happening with 5G and Edge use cases. Over time, NCF will bring unified telco-IT ecosystem, unified execution environment, unified data infrastructure and unified application management.

6.9 Open interfaces

The disaggregation of the RAN and the virtualization of the network functions are expected to continue releases of the mobile networks. As the Open RAN architecture matures and it becomes mainstream, a growing ecosystem will drive the exposure of network APIs for edge computing, automation, and other use cases.

In the 3GPP 5G architecture, the Baseband Unit (BBU) has been decomposed into two functional components, a Distributed Unit (DU) and Central Unit (CU) with the latter being further decoupled into distinct control plane (CU-CP) and user plane (CU-UP) functions. O-RAN provides further disaggregation with new open interfaces. This architecture allows for new deployment models which feature centralized packet processing functions, while allowing for further separation of baseband functions from the (remote) radio unit (RRU/RU).

In addition to that, standardization, and adoption of open fronthaul user and management plane interfaces between the DU and the RU will allow offloading some of the DU functionality, increase the number of RUs and make the deployments scalable for high throughput as expected for future use cases.

All this will enable Open APIs further disaggregation, cloudification of the RAN and multi-vendor interoperability.

6.10 Sub-networks

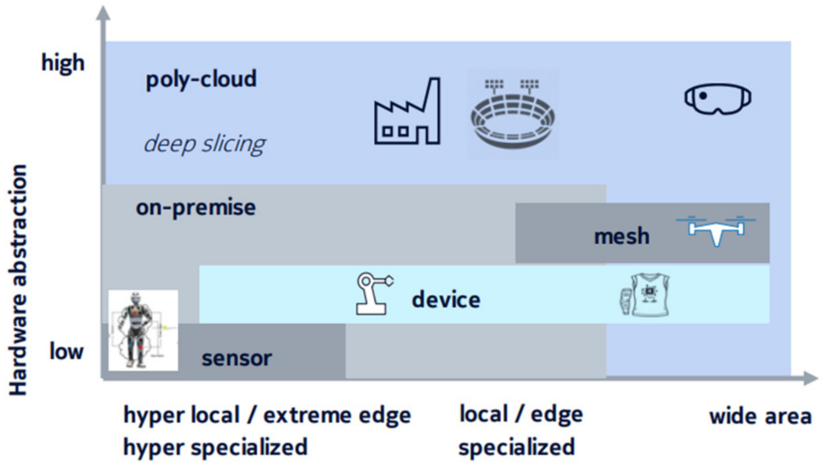
One of the major trends of 6G era networks will likely be the emergence of millions of sub-networks, typically localized and with special attributes of extreme performance optimized for vertical sectors such as industry and health in dimensions such as reliability and low latency. The term sub-networks is defined to consist of several devices connected to an access point and part of a 6G network.

The sub-network can use local optimization mechanisms for sensors and energy consumption as well as support tailored protocol stack (PHY, L2/L3) and air interface. It can operate without continuous connectivity to a wide area network. Such sub-networks may fall on the continuum from on premises/specialized neutral host to federation by MNOs across wide area, thereby enabling options of value chain transformation such as linking production to logistics.

Examples of sub-networks include in-body, in-robot, in-car as well as swarm of drones. Whereas in-body networks will typically be optimized for extreme reliability and low latency in conjunction with high sensor density, optimization of swarm drones' sub-network will be focused on aspects such as link budget performance and ad-hoc cooperation. 6G sub-networks are differentiated in many dimensions including data rate, reliability, availability, and security etc.

One way of classifying a sub-network could be to categorize by the location of the network function on the continuum from hyper-local to wide area and, in a second dimension, by looking at the associated degree of hardware abstraction.

Figure 8: 6G sub-networks classification



From an architectural perspective, sub-networks can be both stand-alone and connected to the wide area networks. Such approach will allow bi-directional off-loading as well as sophisticated schemes of capability discovery. Control plane (CP) functions of both sub-network and wide area network will facilitate interconnections; local CP functionality will be provided by the sub-network. Lower layers of the radio stack may be different from that of the wide area network and local protocols can be converted by an access gateway from internal to external.

6.11 Transport

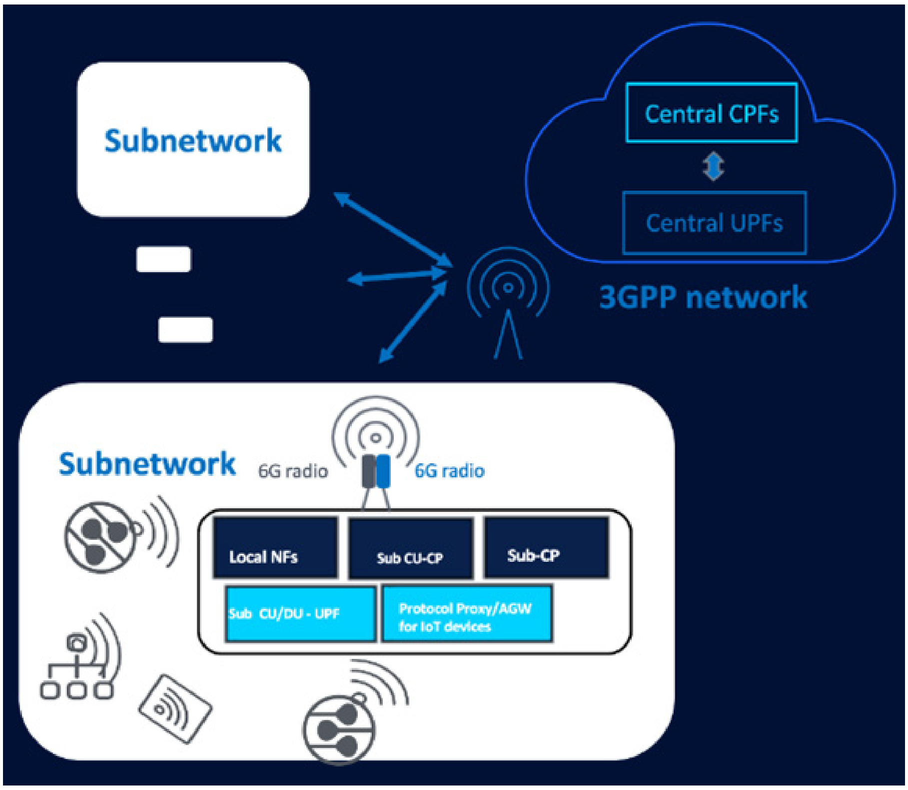
In 6G, there is a need for a versatile transport solution that can support a multitude of architecture and deployment options like distributed, centralized, and virtualized RAN (DRAN, CRAN, and vRAN). Operators will have different network deployment strategies and a versatile transport needs to support different options, ranging from extremely dense urban to remote rural locations. Furthermore, transport needs to support the various requirements defined by different services, including requirements on predictable latency and predictable bitrates. New options like D-MIMO together with packet transport networks designed for statistical multiplexing, will create additional challenges for RAN synchronization and congestion avoidance.

The cases that are expected to be drivers for developing 6G will require very high data rates, generating high volumes of data to be transported between core network and radio sites (macro, street macro, micro/pico-cells, and indoor access nodes). Increasing the air-interface data rates can be done by improving spectral efficiency and by using higher frequencies with wider bandwidth. Higher frequencies will however require increased densification of the radios with a resulting increased densification of the transport to the radio sites. Fiber deployment is not always feasible or cost-effective. When channel propagation conditions allow, wireless backhaul can be an alternative to fiber.

With 5G, there is a trend toward more of CRAN where baseband processing is done in central locations and radios are connected via fronthaul interfaces like CPRI or eCPRI. This is expected to continue with 6G. However, it is also foreseen that the dominating RAN deployment of today, DRAN, where baseband processing is located at the radio site, will be co-sited with CRAN fed radios. This mix of CRAN and DRAN will create demands for a versatile transport solution where the link to the radio site may carry both backhaul traffic as well as fronthaul traffic, with vastly different requirements. Hence, no matter the type of backhaul and fronthaul traffic, it should be able to support radio links operating at any frequency range going from sub-GHz up to sub-THz radios.

Although the air-interface data rate increases, it is not necessary to scale up the capacity of the transport network in the same proportion due the statistical nature of how the services are utilized. It is highly unlikely that many users in different

Figure 9: 6G sub-network interconnection architecture



sectors would require peak data rate at the same time, which enables use of statistical aggregation when dimensioning the transport network. It would also be difficult for the RAN to support many users with peak rate demands and RAN would in such cases likely limit the data rates anyway. This will keep both cost and power down compared with traditional dimensioning for constant peak load. Further, the use of switched packet fronthaul enables CRAN deployments to have automated configuration and allocation of baseband processing resources based on the user needs.

Transport should not be a bottleneck, but it should at the same time not be over-dimensioned compared to the rest of the network and drive cost. It needs to be cost-effective including building on existing infrastructure when applicable, flexible, fast to deploy, and evolve continuously as the network is evolved to meet growing capacity needs and when new services are introduced. Since transport needs to also support more stringent requirements posed by critical 6G services that require for example guaranteed bitrate and latency, the transport should be self-organizing, programmable and support e2e orchestration of network slices.

To achieve this, some level of interaction between transport and RAN and/or core is foreseen as beneficial. For example, sharing of certain information such as, e.g., a RAN scheduler has knowledge about current transport network status (congestion, utilization, latency jitter, etc.) and vice versa. The transport network should have access to QoS-related information for any-haul flows which it can use for prioritization to enable more efficient tools handling congestion, controlled latency and e2e QoS.

6.12 IP Network Evolution

Significant conversations have taken place in 2021 on new use cases that could require enhancements to the IP network. Proposals have been made to numerous domestic and international standards bodies without regard to the current evolution of IP. According to IDC, there are over 20 billion connected devices, with the IT sector alone being a $5.2 trillion industry. The Internet has continued to evolve in meeting the needs of the industry and society. The future will bring increased demand of the Internet and work is underway to ensure a smooth evolution to meet this need. Any new efforts should be “evolutionary” not “revolutionary”.

Work in forums such as the Third Generation Partnership Project (3GPP), Institute of Electrical and Electronics Engineers (IEEE) and Internet Engineering Task Force (IETF) has been underway for years extending the capabilities of the current IP network to meet new requirements. This is being done in an affordable evolutionary approach versus a revolutionary approach.

Areas under study include:

- *Determinism: IEEE 802.1 Time Sensitive Networking*
- *Determinism: IETF Deterministic Networking (detnet), Reliable and Available Wireless (RAW)*
- *Traffic Steering: Segment Routing for IPv6 (SRv6)*
- *Universal Encapsulation: Geneve, GRE, L2TPv3, VxLAN*
- *Multipath: Hybrid ICN, MP-QUIC*
- *In-network computation: IRTF Computation in the Network (COIN)*
- *Low latency: IETF Low Latency, Low Loss, Scalable Throughput (L4S)*

6.13 Security and Trust

Cyber-security, privacy and trust will be a key technology themes of the 6G era to assure societal acceptance of communications in the 2030s. In the next decade, we expect threat vectors will be challenging in several dimensions, including implementation of zero-trust networks, and the increase towards billions of sensors and devices, as well as millions of sub-networks. Architectural disaggregation, multivendor and open-source software play as well as a multi-stakeholder supply chain in general will drive the need for sophisticated security mechanisms and concepts. Not to mention the expected proliferation of AI/ML technologies that will on the one hand side allow novel forms of attacks while, at the same time, they can be leveraged for protection purposes.

Key security technology enablers for the 6G era should include AI/ML as well as advanced ways of automated software coding and automated operations of networks, hardware embedded anchors of trust, privacy preserving technologies and options to assure cyber-security in a post-quantum world. Physical layer security mechanisms may hold some promise in conjunction with energy and compute power constrained devices and sub-networks. Jamming protection will be of pivotal importance with specialized and local 6G sub-network operation.

Current and future generations of mobile networks are being designed to assume increasingly critical roles in industry and society. Some of these roles relate to the potential of 5G and 6G networks in addressing automation across a variety of industries, spanning manufacturing, utilities, public safety, transportation etc.

Network Operators must be able to run their networks in the face of disasters and attacks, for instance to ensure local availability of services despite issues elsewhere. Future networks are also expected to introduce joint communication and sensing capabilities. These capabilities raise a host of security and privacy questions in these new areas, such as who should have ownership and access to sensing data collected by mobile networks. The emergence of a more intelligent and connected network will present new attack vectors and threats. As the world becomes more digitalized, attention to privacy will become more relevant than ever.

Cloud and virtualization technologies hold the promise of flexibility, in principle making it possible to run any function anywhere. These new ways of combining or distributing functions give rise to key security questions in the context of future networks;

for example, who owns the root of trust for a virtualized function, which parties have the capability to observe or influence virtualized functions, who owns the data processed in a network function, and hence what level of security is needed. Today security assurance methodologies put a lot of focus on product security. In the future, security assurance methodologies should be able to take the whole product lifecycle into account, including configuration and live operation of the products and systems.

It can be expected that confidential computing is going to be a basic building block for security in the cloudified and virtualized world. Confidential computing will also form the basis for Root of Trust-based identities. The secure identities in turn will be important for evolving the protocols stacks. Data privacy grows in importance as more data is transferred in communication systems, and protocol stacks need to evolve accordingly to become increasingly privacy preserving. New tools are expected to be available to help in enhanced assurance, one of them is using AI/ML capabilities for detecting threats and dynamically respond to them.

Artificial Intelligence is expected to improve operational efficiency for network operations, as well as revolutionize the ability of services to avail of intelligence in the network. Consequently, we need to consider two aspects: security for AI and AI for security.

The first aspect raises the concern that the logic of AI component execution is often not easily understandable by humans. Further, the more sophisticated AI models are often dynamic, complex, and continuously adapting to changing contexts, but acting as a black box from a human perspective. This makes it difficult to judge its trustworthiness. Work on explainable AI is an important goal.

The other aspect of AI is its significant potential in improving security. The security community is increasingly looking into how AI can help with threat detection and threat analysis. Threat analysis can thus be automated with AI, and it is also conceivable that AI can help in dynamically mitigating some threats.

Privacy continues to be high on the agenda.

Infrastructure and services must be built in a way that they do not leak user information. Information shall only be released to parties that truly need it and must be protected with technical means such as encryption or confidential computing. Data governance becomes even more important aspect of privacy protection allowing for access rights across domains and information security

An important aspect of security assurance is to set up a framework with well-defined processes for security assurance that are accepted by all stakeholders and standardized globally.

Connected devices (IoT) security

By 2026, there is estimated to be more than 26 billion connected devices in the world. IoT security must be built in from the beginning. When it comes to IoT, security requirements are unique. Connecting devices is different from connecting individual people and personal computers. To verify its identity, an IoT device can't simply enter a password as a person would. Similarly, the systems that run our PCs are regularly updated, but IoT has to work all time. A reliable infrastructure is especially indispensable for mission-critical applications. IoT security management must be approached in new ways,

Figure 10: Technology Objectives for Secure Trustworthy Next G Systems (Source: 5G Americas Member Company)

Technology objectives for secure trustworthy Next G systems

Security assurance and defense

Enhanced assurance for the whole product lifecycle and across services end-to-end

ML/AI capabilities for threat detection and response

Service availability

Enhanced observability for network performance

Efficient and robust resource provisioning for critical services

Secure identities and protocols

Root of Trust -based identities for software and hardware

Privacy preserving protocol stacks

Solutions built on Confidential Computing

Confidential Computing for network slices

Data protection for third party functionality, including confidential handling of datasets and model parameters for ML moving from reactive and manual to proactive and automated. The sheer volume of devices that will get connected calls for security automation, and enhanced security analytics capabilities.

The CTIA IoT device cybersecurity certification program provides an industry baseline for device security on wireless networks that provides a foundation for secure wireless IoT systems.

Finally, Quantum Technologies will form an important element of building trustful networks in 2030 networks. This is a hot research area. A separate addendum is included on quantum computing, cryptography, and communications to discuss the status and potential future applications.

6.14 Quantum Computing, Cryptography and Communications

Cryptographic algorithms and security protocols are among the main building blocks for constructing secure communication solutions in the cyber world. Mobile networks are critical infrastructure and heavily use advances in cryptographic algorithms and protocols to ensure the security of the information in the communication and privacy protection for the individuals.

Software performance is essential for software implementations in virtualized deployments.

Currently used algorithms are not suitable for future deployments as they are slow in software, do not support 256-bit keys, and only support 32-bit media access control (MACs). Third Generation Partnership Project Systems Aspect 3 (3GPP SA3) and European Telecommunications Standards Institute Security Algorithms Group of Experts (ETSI SAGE) have therefore started working together on new virtualization-friendly algorithms suitable for later 5G releases and 6G.

The new algorithms to be introduced to 3GPP will likely support only 256-bit key length and offer at least 64-bit tags. While 128-bit algorithms will be practically secure against quantum computers, cellular networks are increasingly classified as critical infrastructure. Already today, governments and financial institutions often mandate more than 128-bit security level for protection of their communication.

As networks evolve, new cryptographic algorithms and signatures must be considered that anticipate the threat surface exposed by the possibility of quantum computing technologies within the lifespan. This will require the adoption of quantum-safe or post-quantum symmetric and asymmetric cryptography.

Small quantum computers already exist. However, it is still uncertain when or if quantum computers capable of breaking these cryptographic algorithms will be built. While significant threats from quantum computing has a low likelihood within the next 10 years, this cannot be assumed indefinitely so, given the maturity of quantum safe cryptographic technologies, post-quantum algorithms should be introduced in networks by 2030. 3GPP will likely introduce quantum-safe algorithms long before quantum computers even get close to affecting the security of 3GPP systems. Introducing non-standardized cryptographic algorithms likely introduces more risks than it solves, and both 3GPP and IETF have taken the decision to wait for NIST standardization of post-quantum cryptography (PQC) algorithms, which is already in the final round and will be ready in 2022-2024. After that, IETF will standardize the use of PQC algorithms in datagram transport layer security (D)TLS, Internet key exchange version two (IKEv2), X.509, JOSE and hybrid public key encryption (HPKE) and as soon as this is done, 3GPP will introduce the new updated IETF requests for comment (RFCs).

Researchers in quantum networking are looking at quantum key distribution (QKD), which would theoretically be a provably secure way to do unauthenticated key exchange. QKD is however not useful for any other use cases such as encryption, integrity protection, or authentication where cryptography is used today as it requires new hardware and is also very expensive compared to software-based algorithms running on classical computers.

In a well-written white paper, the UK government is discouraging use of QKD because it will introduce new attack vectors, its hardware dependency is not cost-efficient, and it has limited scope making it unsuitable for future challenges. Post-quantum cryptography is recommended as a better alternative.

US government also has a similar dim view of QKD. National Security Agency-Central Security Services (NSA-CSS) in its write-up on QKD lists 5 key drawbacks to discourage the use of QKD:

- *Quantum key distribution is only a partial solution*
- *Quantum key distribution requires special purpose equipment*
- *Quantum key distribution increases infrastructure costs and insider threat risks*
- *Securing and validating quantum key distribution is a significant challenge*
- *Quantum key distribution increases the risk of denial of service*

NSA points to PQC as a more cost-effective and easily maintained solution than QKD and does not support the usage of QKD or QC to protect communications in National Security Systems

The National Institute of Standards and Technology has long functioned as a global standardization organization for cryptographic algorithms. NIST standardizes algorithms in open competitions, inviting contributions from academia all over the world. Both Advanced Encryption Standard (AES) and Secure Hash Algorithm 3 (SHA-3) were designed by researchers from Europe. Recently, the Internet Research Task Force Crypto Forum Research Group (IRTF CFRG) has complemented NIST as a global cryptographic Standards Developing Organization (or SDO) and NIST has introduced many of the CFRG algorithms within their own standards.

With the application of quantum mechanics in computing and communications, it is possible to achieve trustworthy networks of future. Quantum networks use the quantum properties of photons to encode information. They will one day be able to distribute entanglement across several nodes that are composed of different quantum technologies, separated by a range of physical distances. Local quantum networks (intranets) may require diverse components such as quantum interconnects and quantum memories. Terrestrial quantum networks may include ground-, air-, and sea-based platforms. Most quantum protocols require support from a classical layer, so interfacing a quantum network with classical components will be critical. A fully functional network will require advancements in several enabling technologies such as sources, detectors, transducers, and repeaters for quantum states of light and matter.

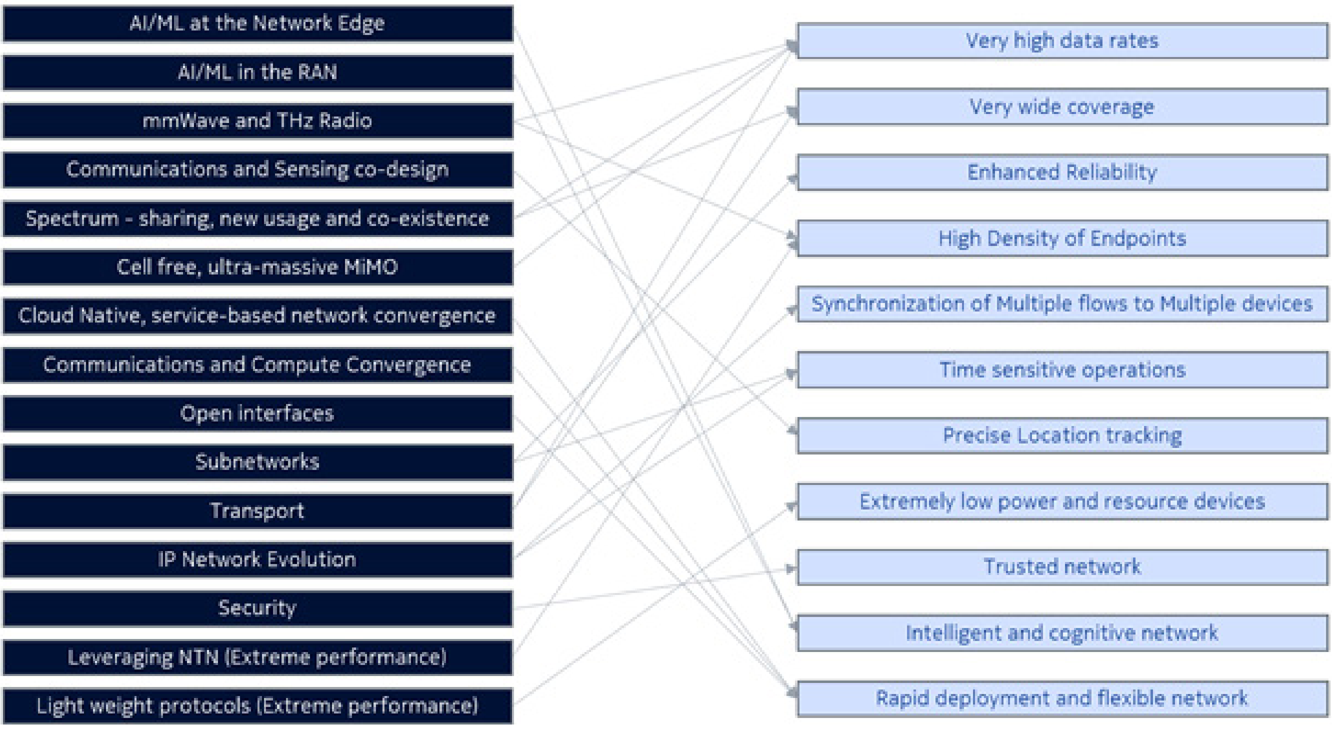
Qubits or quantum bits are the fundamental building block for quantum information processes. Whereas conventional computers store and process data as a series of ‘1’s and ‘0’s, quantum computers use the properties of a quantum system, such as the polarization of a photon or the spin of an electron.

Quantum entanglement is a quantum mechanical phenomenon in which the quantum states of two or more objects must be described with reference to each other, even though the individual objects may be spatially separated. Perfectly entangled objects behave as a single quantum state regardless of how far apart they are and manifest correlations that cannot be obtained classically.

Because of the single qubit non-cloning theorem, any manipulation of the quantum key will change the quantum state or destroy the information carrier itself, so that the information obtained by the eavesdropper is meaningless. We can use the quantum state as the communication key to achieve “absolutely safe” information transmission.

Entanglement is the essential resource that enables nearly all quantum technology, but is very fragile, making it hard to create and maintain over long times and across large distances. The direct approaches are limited to much less than 500 km, even under the most optimistic assumptions for technology evolution.

Figure 11: Potential technologies to technology requirements mapping



There are two primary channels over which to transmit the photons: optical fiber and free space. Each of these has challenges and opportunities.

A quantum repeater is a technology that enables and extends the range of fiber-based quantum entanglement distribution among the distant (and uncorrelated) nodes of a quantum network without suffering from unbearable signal losses. It relies on entanglement resources, projective measurements, and quantum memories.

Satellites have been recognized as one of the best methods for achieving global-scale quantum communication with current or near-term resources. Using satellites is advantageous since the majority of the optical path traversed by an entangled photon pair is in free space, resulting in lower loss compared to ground-based entanglement distribution over atmospheric or fiber-optic links.

Potential applications of Secure Quantum Communications include banking, national security, energy delivery infrastructure, securing personal identifying data (PID) and other sensitive data, Voice over Internet Protocol (VoIP), Blind Quantum Computing, Quantum Sensor Networks, Precision Clock Synchronization, Distributed Quantum Computing.

7. North American Leadership

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.

7.1 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 kickstarted 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 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 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:

- O-RAN Alliance
- Open RAN Policy Coalition
- ATIS
- Next G Alliance

7.2 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 – an 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*

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. Advanced wireless research portfolio within NSF have created a program named RINGS (see section 2.1.1) leveraging the PPP model to support NextG network systems research.

When larger scale funding is available for 6G research, 6G collaborative research projects with many industry partners could be envisioned.

7.3 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. Furthermore, it is important to have close collaboration between various forms of research and the standardization process to ensure innovation flourishes all the way from the research entities to the final standardized deployments. Common goals and visions of success from the innovative leading North American stakeholders can help ensure the success of the next generation wireless technology.

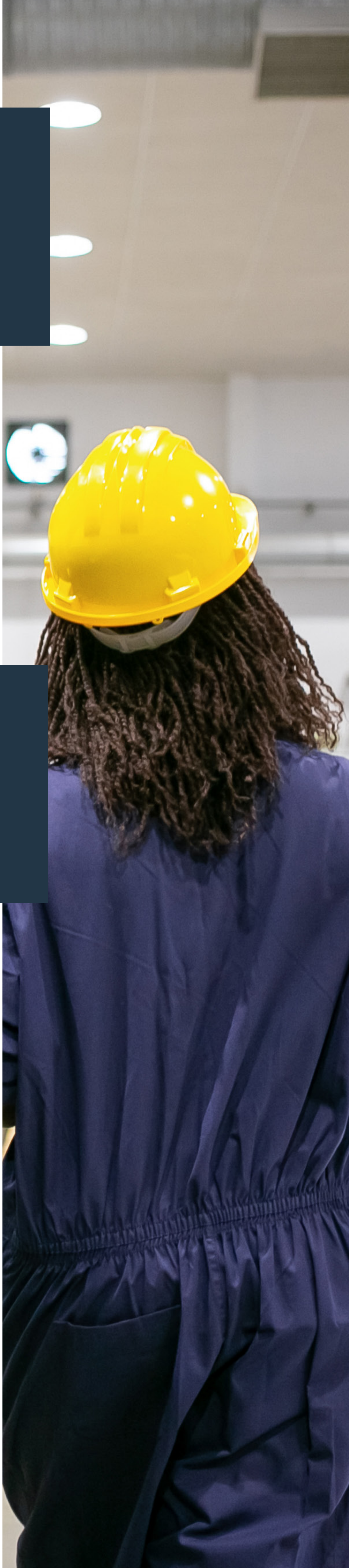
8. Regulators in North America Help Industry Maintain Leadership

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 site processes, private public partnerships and opening 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.

Conclusion and Recommendations

This paper provided an overview of the industry research across the globe looking at the evolution of mobile wireless networks. While many are already calling it “6G”, whatever moniker that is eventually used will still be 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 remain 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 use cases 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 dynamically adapt technology and evolve beyond 5G and into the next G. 5G Americas recommends the innovative North America mobile wireless industry continue to take action and prioritize wireless innovation and evolution ensuring leadership in this great wireless communications industry for decades to come.



Appendix A

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 more details on the use cases that are being identified for the mobile wireless industry to address both today and tomorrow.

Detailed Use cases descriptions

UC 1 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: Simulated sensorimotor and cognitive experience surrounding the user in an artificially created world, 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 virtual and artificially created content on top of the real world. The user can interact with both the real world and virtual components or augmentations.*
- *MR: By combining bits of VR and AR together, MR seamlessly blends the user's real-world environment and virtually 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.

Applications of VR: Learning and social interactions virtually have become more predominant after the COVID-19 pandemic. In fact, education and training via VR services can allow learners to develop skills remotely and without real-world risks and failures. This is especially useful in situations where life or death is at stake. Furthermore, beside learning and training, VR can serve multiple entertainment services such as video games and fully sensory movies and events. In fact, the introduction of VR services to such experience will transcend standard gaming and movie experiences to a fully immersive and seamless experience. Also, the virtual experience need not be fictious, attending concerts, and sports events have become one headset away.

Applications of AR: While AR might share some applications with VR such as spatial-audio and multiparty calls as well as 3D video games on handheld devices, AR's prevalent importance rises in mission-critical applications like healthcare, industry, and vehicular/aerial navigation. Taking a complex manufacturing plant as an example, technicians dispatched to solve a problem can look at a machine on the factory floor and examine the status of machine components superimposed on top of the normal camera view. As the technician moves around, they can examine 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.

Applications of MR: MR's framework allows adopting various applications from VR and AR in a mixed virtuality and reality paradigm. 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 in terms of care and surgery. 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. Regarding remote surgery, a surgeon can physically or remotely perform a telesurgery medical procedure while collaborating with other remote surgeons. The MR interface allows to deliver all participating parties with all the required medical information to ensure a smooth and hazard free surgery.

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. First, given that XR services need to guarantee a joint high quality of visual and haptic components, stringent high-rate (both in uplink and downlink) and high-reliability low latency communications are imposed on the wireless network. Second, different types of sensing capabilities need to be leveraged. For instance, high-precision and high-resolution information that portray the 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. Third, the aforementioned sensing data and network communication data should be intelligently processed and then fed to the real-time ML and AI interfaces to optimize and fine tune the performance.

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.

UC 2 Holographic Teleportation

Holographic Teleportation is the evolved version of MR that is starting to see light with the advancements seen in 3D imaging. In particular, holograms are 3D images of a physical object captured via 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.

The incorporation of the five senses in holographic teleportation leads to more stringent requirements on the wireless network than XR. Transmitting 3D holograms necessitates Tbps-level data rates and microsecond-level latency. Furthermore, a tight synchronization between five senses is also necessary to guarantee a rich multi-sensory experience and to incorporate the concept of the Internet of Senses. Additionally, the extreme low latency requirements are also complemented with low jitter requirements to ensure that the users do not fall into motion sickness.

UC 3 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 with adjustments based on whether the surgeon is wearing a head mounted display device or interacting with a hologram. Using a Human System Interface (HSI), the surgeon proceeds with the operation using haptic-enabled robots at the patient-end that 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.

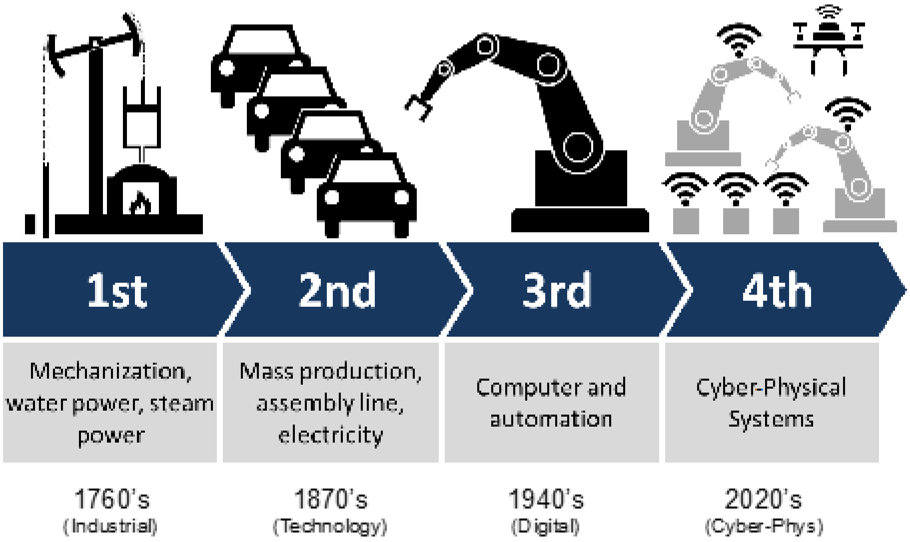
Another example is remote industrial management that involves remote real-time monitoring and control of industrial machinery. Remote control is enabled using tactile sensors providing kinesthetic feedback from the machine to the operator. Tactile feedback is augmented real-time audiovisual information, 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.

UC 4 Industry 4.0

Throughout the course of history, the world's technology has evolved 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). CPSs are large-scale systems that seamlessly integrate physical and human elements through a cyber layer that allows for connectivity, sensing, and data processing. Smart power systems, smart transportation systems, and the Internet of Things are all examples of CPSs (IoT).

Figure 12: Industrial Revolutions



Of particular interest, Industry 4.0 is 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.

The transition to Industry 4.0 is resulting in highly autonomous machine and robot operations that require only occasional human intervention. As a result, manufacturing processes requiring high precision and accuracy necessitate novel instantaneous control mechanisms. Henceforth, to achieve the full autonomy desired in Industry 4.0 and guarantee an end-to-end digitization the concept of a digital twins has recently emerged (described in section 4.2). Digital twins enable creating a virtual copy or model of complex physical assets in the real world., Moreover, digital twins are used to make predictions on the evolutionary dynamics and future states of large-scale systems, as well as to control them in real time.

UC5 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. Providing such high-fidelity representation of the operational dynamics puts a burden on the underlying wireless network. The physical counterpart can only be fully replicated by allowing real-time synchronization between cyberspace and physical spaces. We envision that beyond 5G systems need to be able to fulfill the stringent requirements of digital twins in terms of bandwidth, latency, synchronization, and bi-directional reliability.

Beside Industry 4.0, digital twins can play a prominent role in 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.

UC 6 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 give 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, sick animals can be identified 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*

UC7 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. 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 , with V2X (Vehicle-to-Everything) communication technology, 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. Here, we list some promising use cases for the future transportation vertical market:

- *Improving efficiency of transportation systems*
  - » *Car platooning*
  - » *Speed harmonization*
  - » *Smart intersections*
- *Advanced Driver-Assistant Systems*
  - » *See-through*
  - » *High-definition sensor sharing*
  - » *Real-time high-definition maps*

- *Improving transportation safety*
    - *Left turn assist*
    - *Vulnerable road user discovery*
- *Autonomous Driving-related*
    - *Remote driving assistant for autonomous vehicles*
    - *Cooperative maneuver of autonomous vehicles*
    - *Cooperative perception*
    - *Cooperative safety*
- *Intelligent Transportation Systems*
    - *Faster emergency response and road operators*
    - *Smart highways with autonomous driving lanes*
    - *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. Those 5G systems are designed to support 10 ms end-to-end (E2E) latency, 1 ms physical (PHY) layer latency and 99.999% reliability.

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.

UC 8 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 disjointed 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*

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.*

UC 9 First Responder/Emergency Services

Public Safety (PS) with Emergency Service Response (ESR) requires a reliable (in terms of 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 13: 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 can be used in the form of stored and forward transmission via network connected body cameras and from police vehicles to dispatch control centers, where the camera can be remotely controlled.

UC 10 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 14: Future networks to serve national security use cases with speed, precision, and efficiency.

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”. 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 15 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 15: 5G Use Cases for DoD, highlighting those being prototyped today

Additional Horizontal UCs (across verticals)

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 or solely terrestrial-based Internet protocols. Note that today's air and 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*

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.

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.

Massive Scale IoT Networks

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

- *Smart cities sensors, such as 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.

Additional Requirements

Industry 4.0 requirements

- *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.

Appendix B

Review of Global Activities

European Efforts

6G Genesis Flagship

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 and 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€.

Korea Efforts

In March 2021 Samsung Electronics announced that Hyoungjin Choi, Principal Engineer at Samsung Research was appointed as the Chair of the Vision Group on IMT towards 2030 and beyond (6G) at the International Telecommunication Union – Radiocommunication (ITU-R) Working Party 5D, WP 5D Assembly, held online from March 1 to 12.

In May 2021 Dr. Jeongho Jeon, engineering manager in the Standards and Mobility Innovation Lab in Samsung Research America, was elected as a Vice Chair of the Technology Working Group within the ATIS Next G Alliance for a two-year term. This election outcome reflects the leadership that Samsung has demonstrated in developing the 4G/5G market and driving 6G research.

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

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