# NextG

## Communications Research and Development Gaps Report

November 2023

Nada Golmie, nada.golmie@nist.gov
Alhussein A. Abouzeid, aabouzei@nsf.gov
Thyagarajan Nandagopal, tnandago@nsf.gov
Murat Torlak, mtorlak@nsf.gov
Marc Leh, mleh@corneralliance.com
Miller Higgins, mhiggins@corneralliance.com

Published by

NIST COMMUNICATIONS TECHNOLOGY LABORATORY

NIST SPECIAL PUBLICATION 1293

NIST Special Publication
NIST SP 1293

# NextG Communications Research and Development Gaps Report

**National Institute of Standards and Technology & National Science Foundation**

**Nada Golmie**
Communications Technology Laboratory
National Institute of Standards and Technology

**Alhussein A. Abouzeid**
**Murat Torlak**
Directorate for Computer and Information Science and Engineering
**Thyagarajan Nandagopal**
Directorate for Technology, Innovation and Partnerships
National Science Foundation

**Marc Leh**
**Miller Higgins**
Corner Alliance
Washington, DC

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.1293

November 2023

Published by:

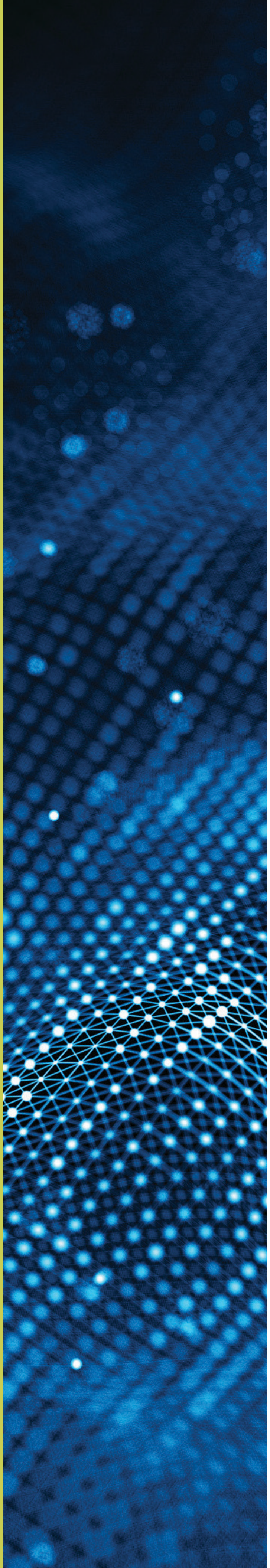
**U.S. Department of Commerce**
Gina M. Raimondo, Secretary

**National Institute of Standards and Technology**
Laurie E. Locascio, NIST Director and Under Secretary of Commerce for Standards and Technology

Research sponsored by

National Institute of Standards and Technology [SP] [1293]
Natl. Inst. Stand. Technol. [SP] [1293], 61 pages (November 2023)
CODEN: NSPUE2

This publication is available free of charge from: https://doi.org/10.6028/NIST.SP.1293



# Contents

# Introduction

As communications technology evolves beyond fifth-generation wireless systems (5G) and technology capabilities supporting next-generation communications systems (NextG) become more widespread, the research and development (R&D) community faces an opportunity to identify long-term technical gaps that, if addressed, could scale innovations across the wireless communications industry over the next 20 years. To help understand the major challenges affecting long-term communications and computing research, the National Institute of Standards and Technology (NIST) engaged stakeholders with diverse expertise from organizations representing academia and industry (e.g., wireless carriers, equipment and infrastructure manufacturers, and providers of applications and services) to identify high-impact technology innovations and research questions affecting NextG systems. NIST partnered with the National Science Foundation (NSF) and invited stakeholders to provide insights on which measurement, technology, and management challenges need to be addressed in order to deliver new, differentiated communications and computing services using NextG systems.

This report describes several of the significant technology gaps for R&D entities to consider in their long-term planning to support sustained innovation of NextG systems. This report does not intend to prescribe specific R&D investment recommendations or comment on the current or planned initiatives of the specific industry, government, or academic organizations. Data presented in this report builds on the "Future Generation Wireless R&D Gap Analysis" published by NIST in 2018 (NIST SP1219)[1] and is intended to serve solely as a knowledge product. This document summarizes the results of over 18 months of NIST stakeholder engagement with NextG communications and computing experts. This effort prioritizes technical needs that align with the following criteria:

- **R&D shortfalls —** These are issues that industry, academia, and standards bodies are not already researching or research issues that could benefit from additional resources.
- **Long-term —** Addressing identified gaps scale to a 10-20 year time horizon.

[1] Nada Golmie, David Cypher, Marc Leh, Darcy Ziegler (2018) Future Generation Wireless Research and Development Gaps Report. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 1219. https://doi.org/10.6028/NIST.SP.1219

- **Accelerates convergence of communications and computing systems** — Technical capabilities may be leveraged by traditional and new entrants across the NextG hardware, software, and network ecosystem.
- **Alignment with Federal R&D capabilities** — This represents a gap that is high-risk / high-reward, lacks immediate profit incentive or feasibility, and is, therefore, best suited for government research.

# Approach

In November 2021, the NIST and NSF team began evaluating future wireless research challenges, gaps, and opportunities by reviewing existing literature and conducting market research. NIST and NSF reviewed materials such as wireless communications standards publications, scientific journals, R&D strategic plans, corporate white papers, technology policies, and editorial content to understand the current needs and priorities of the NextG research community. A full list of reports reviewed to inform the findings, topics, and structure of this report is provided in Appendix A.

After this preliminary step, the team conducted a series of one-on-one interviews with key stakeholders to build on market research findings. NIST and NSF interviewed communications R&D experts representing organizations across private industry, the federal government, academia, and non-profit research consortia. The purpose of the interview process was to understand R&D organizations' current research activities and priorities, short-and long-term R&D challenges, and their key requirements for future communications systems. NIST and NSF also recruited a variety of R&D organizations to participate in larger working group meetings that would expand and provide feedback on preliminary findings collected during one-on-one interviews.

In April 2022, NIST and NSF convened a public working group (Working Group) consisting of over 50 stakeholders to develop an expanded, more detailed set of long-term R&D gaps and questions. In preparation for monthly Working Group meetings held between April and October 2022, NIST and NSF developed a data collection survey for stakeholders to prioritize NextG wireless communications research verticals and specifically identify the most impactful challenges for long-term communications system innovation. Based on this input, three panels were organized to discuss gaps and opportunities related to NextG Hardware and Higher Frequencies; Joint Communications and Sensing; and Data Privacy, Sharing, and Availability; as well as other research topics. Each meeting began with subject matter experts providing opening remarks that answered the following questions:

- **What do you see as the most impactful technology innovation related to NextG communications systems in the next 15-20 years?**
- **What can the R&D community begin working on today to help advance this innovation? What technical dependencies or gaps need to be addressed in the near term to support this long-term innovation?**

Prior to each Working Group meeting, NIST and NSF issued a pre-event survey to ask participants to identify measurement, technology development, and deployment gaps associated with these topics. During the open group discussion, participants provided feedback on panelist remarks and identified the key themes. Working Group participants also reviewed meeting summary reports and provided written input on topics discussed during monthly panels to ensure NIST and NSF captured technically-accurate, relevant conclusions in this report.

Results from this iterative approach were organized into the following sections:

1. **Trends and Drivers Affecting the Need for NextG Innovations:** Provides context for how R&D organizations may view the standards development process, U.S. industrial policies such as the "Creating Helpful Incentives to Produce Semiconductors (CHIPS) for America Act",[2] and other trends affecting the communications and computing industries in relation to NextG technology innovation.

2. **Hardware and Higher Frequency R&D Gaps:** Describes a variety of technology enablers, gaps, and research questions associated with hardware capabilities and the higher frequency spectrum required for NextG use cases.

3. **Spectrum Science and Sharing R&D Gaps:** Describes key spectrum measurement, sharing, re-use, and other technology development challenges to ensure occupied and new spectrum bands are maximized to their full utility while accounting for data-intensive NextG applications poised to overload existing spectrum capacity.

4. **Joint Communications and Sensing R&D Gaps:** Describes research challenges and opportunities associated with integrating radar sensing capabilities into broadband and internet-based networks required for a more adaptable, resource-efficient, ubiquitously connected NextG communications experience.

5. **Artificial Intelligence and Machine Learning R&D Gaps:** Describes research challenges and opportunities for expanding the use of data science, machine learning, and artificial intelligence capabilities across all components of NextG systems to optimize network resource allocation, improve visibility into network performance, and enable new applications related to machine-to-machine communications, immersive user experience, and other requiring automated data collection and processing.

6. **Data Availability, Use, and Privacy R&D Gaps:** Describes governance and technology research challenges associated with acquiring, managing, processing, and securing new data sources necessary to support NextG communications applications.

7. **NextG Network Architectures R&D Gaps:** Describes challenges related to more flexible access technologies, network designs, protocols, policies, measurement, testing, and data processing technologies required to exploit the increasing diversity of devices and applications supported by heterogeneous NextG networks.

8. **Non-Terrestrial Network R&D Gaps:** Describes technology challenges related to developing non-terrestrial network infrastructure such as satellites and Unmanned Aerial Vehicles (UAVs) and integrating these technologies with terrestrial architectures to create more flexible, higher-capacity, and on-demand communications systems.

9. **Sustainable and Energy Efficient Networks R&D Gaps:** Describes challenges related to optimizing network architecture, hardware configuration, software controls, and energy consumption metrics to support more power-efficient, sustainable NextG system operations.

[2] "H.R.6395 - 116th Congress (2019-2020): William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021." Congress.gov, Library of Congress, 1 January 2021, https://www.congress.gov/bill/116th-congress/house-bill/6395.

# Trends and Drivers Affecting NextG Innovations

NextG is considered a critical technology area for many sectors across the economy, and specifically, for national defense.[3] The main challenges facing communications systems going forward relate to **increasing their capacity and agility.** According to the "Decadal Plan for Semiconductors 4",[4] advances in communications systems need to enable the transmission and receipt of "all stored data of 100-1000 zettabytes per year at the peak rate of 1 Terabit-per-second at less than 0.1 nanojoules per bit." This performance requirement represents the intersection of many complex hardware and software engineering challenges related to network design, computing, data analytics, and sustainability. The added intelligence and agility sought for communications systems intends to optimize resource utilization across increasingly diverse communications networks, improve network performance, and enable new applications in an energy-efficient manner.

## Synergy Between Advanced Communications R&D and NextG Semiconductor Manufacturing

Next generation microelectronics can deliver significantly higher capacity and agility for future communications systems. However, before that is realized, several breakthroughs in wireless communications R&D, especially those related to circuit design, packaging, edge network optimization, modeling, and validation are needed. At the time of writing of this report, public and private R&D organizations are investing unprecedented amounts of funding to drive innovation across all sectors of the U.S. semiconductor industry. In December 2020, as part of the William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021 (NDAA), Congress passed into law funding programs supporting the bipartisan CHIPS for America Act. The NDAA authorized the Department of Commerce (DOC), DOD, and the Department of State (DOS) to fund R&D activities

[3] U.S. Department of Defense (2023) National Defense Science & Technology Strategy 2023. (U.S. Department of Defense, Washington D.C.) Retrieved from https://media.defense.gov/2023/May/09/2003218877/-1/-1/0/NDSTS-FINAL-WEB-VERSION.PDF

[4] SRC (2015) Decadal Plan for Semiconductors 4. Retrieved from https://www.src.org/about/decadal-plan/decadal-plan-full-report.pdf

supporting more capable, complex, and productive design and manufacturing of semiconductors in the United States. R&D organizations such as DOC NIST have identified strategic priorities to innovate the design of next-generation semiconductors and increase the manufacturing capacity and quality of the domestic microelectronics supply chain. Information and communication technologies (ICT) make up over 70% of the semiconductor market share and therefore communications chips will benefit from enhanced semiconductor research and funding.[5] The following sections describe how advanced wireless communications technologies can improve semiconductor manufacturing processes, and how increased production of higher-performance communications chips can drive innovation across NextG wireless communications capabilities and use cases.

Increased demand for systems that communicate, store, analyze, and secure information requires long-term technical innovations such as new channel models that characterize high-frequency spectrum; radio hardware that sense and make decisions based on dynamic environmental conditions; artificial intelligence or machine learning processes that enable faster, higher-capacity, and more energy-efficient networks; and security models that support privacy and confidentiality while interconnected systems leverage sensitive data. The U.S. communications chip design and manufacturing industry stands to benefit greatly from combined investments in semiconductor manufacturing processes and foundational R&D efforts in communications technology.

The strategic goals described in publications such as the "Strategic Opportunities for U.S. Semiconductor Manufacturing"[6] and the "CHIPS for America: A Strategy for the CHIPS for America Fund"[7] underscore the need for research organizations to advance communications infrastructure and emerging technologies. To meet the demand for faster and more efficient wireless communications, there is a need for high-performance communications chips that can handle large amounts of data and maintain signal, power, and thermal integrity. Smart manufacturing processes fabricating and packaging next-generation chips also require new communications modeling, testing, validation, and hardware capabilities to ensure the reliability and performance of the end product. Advanced wireless communications capabilities, such as new models to synchronize machine learning algorithms with the radio frequency (RF) environment, in-line metrology to inspect wafer defects, and sensing systems that enable contextual awareness across various "Smart Fab" processes, represent manufacturing infrastructure tools critical to producing next-generation chips used across every sector of the economy.

One of the key challenges in manufacturing communications chips is the need to model and simulate semiconductor materials, designs, and components. The technologies used in wireless communications are constantly pushing to higher frequencies and denser packaging of circuits. As a result, there is a need to model and control signal, power, and thermal integrity. Simulators for future designs must have the capability to model multiple physical effects in large heterogeneously integrated systems. This requires sophisticated modeling and simulation tools that can accurately predict the behavior of these complex systems.

The need for advanced modeling and simulation tools is particularly important when it comes to the manufacturing process for communications chips. Physical models often do not meet the expectations

[5] SRC (2015) Decadal Plan for Semiconductors 5. Retrieved from https://www.src.org/about/decadal-plan/decadal-plan-full-report.pdf

[6] NIST (2022) Strategic Opportunities for U.S. Semiconductor Manufacturing. (U.S. Department of Commerce, Washington, D.C.), NIST CHIPS Series Report 1000, 1st Ed., Vol. 1. Available at: https://doi.org/10.6028/NIST.CHIPS.1000

[7] NIST (2022) CHIPS for America Strategy. (U.S. Department of Commerce, Washington, D.C.), Available at: https://www.nist.gov/document/chips-america-strategy

of NextG manufacturing processes, and there is a need for digital/virtual twins that can model each operation to improve overall manufacturing yield and reliability. By creating virtual models of the manufacturing process, engineers can test and optimize their designs before they are built, reducing the time and cost associated with physical prototyping.

Another challenge in manufacturing communications chips is the massive amounts of data that are processed during the semiconductor value chain. Modeling tools need to make decisions on these large, disparate data sets to ensure that the end product meets the necessary performance and reliability requirements. This requires advanced machine learning and data analysis tools that can analyze the data and provide insights into the manufacturing process.

In addition to these challenges, there are also specific technology innovations that are needed to support NextG communications chip design, testing, and manufacturing. One of the highest priority R&D technology needs is the development of new materials that can handle higher frequencies and densities. These materials need to have low loss and high thermal conductivity to ensure reliable and efficient operation.

Another key technology need is the development of new packaging technologies that can handle the increasing complexity of communications chips. These packaging technologies need to be highly integrated and provide high electrical and thermal performance. This requires innovations in materials, designs, and manufacturing processes.

Finally, there is a need for advanced testing and measurement technologies that can accurately characterize the performance of communications chips. This requires sophisticated equipment and techniques that can handle the high frequencies and densities of modern communications chips. This includes technologies such as millimeter-wave (mmWave) testing and advanced optical measurement techniques.

The manufacturing process for communications chips is a critical aspect of the wireless communications industry. By addressing these challenges and investing in the necessary R&D, the wireless communications industry can continue to push the boundaries of what is possible and deliver faster, more efficient, and more reliable wireless communications solutions.

# Wireless in Support of the Semiconductor Manufacturing Process

Semiconductor manufacturing requires advanced communications technology to support each step of the supply chain.

NextG chips offer greater network capacity, agility, and application potential for semiconductor manufacturing. Core Chips Manufacturing Challenges addressed by NextG Communications R&D:

- Modeling and simulation of semiconductor materials, design, and components
- Modeling of entire manufacturing processes via digital/virtual twins
- Development of new materials optimized for high frequency spectrum propagation and signal processing
- Advanced measurement and testing of semiconductor quality and performance


- Wireless communication enable real-time collaboration between design teams, regardless of their location. Cloud-based design tools can allow simultaneous access and edits to the design templates, speeding up the process. https://ieeexplore.ieee.org/document/8939356
- Wireless communication can be used to control the machinery used in the manufacturing process. This allows for real-time adjustments and precise control of equipment, leading to a more efficient process and higher quality chips.
- Wireless communication can automate data collection during testing and validation, providing real-time feedback to engineers. Chip developers may leverage communications-equipped IoT devices and wireless sensors to gather, transmit, and receive data about the chips' performance under different conditions.
- Automated systems can use wireless communication to control the packaging process by scanning chips to verify their quality before packaging, tracking the quantity of chips in each package, and managing the inventory of packaged chips.
- Automation can also reduce the risk of damage during packaging. https://ieeexplore.ieee.org/document/8939356

Wireless communication can help manage and coordinate the assembly line. This can include controlling the machinery used in assembly, tracking the progress of chips through the assembly line, and automatically adjusting the assembly process based on real-time data.

*Figure 1: Wireless in Support of the Semiconductor Manufacturing Process*

# CHIPS Act

In 2021, the U.S. Congress passed the Creating Helpful Incentives to Produce Semiconductors for America Act (CHIPS ACT)(Pub. L. No.116-283). This legislation responds to the ongoing chip shortage and a decrease in semiconductor manufacturing capacity in the United States from 37% in 1990 to 12% today.[8] This legislation intends to strengthen U.S. positioning across all elements of the semiconductor supply chain, support new microelectronic manufacturing capabilities, and develop a more capable manufacturing workforce. Partnerships between industry and government seek to create better methods for research and development of new semiconductor chips. The DOC, U.S. DOD, and U.S. DOS are the primary actors in carrying out CHIPS Act activities.

The CHIPS Act International Technology Security and Innovation (ITSI) fund managed at the U.S. DOS provides $500 million for international information and communications technology security and semiconductor chain activities in support of Logic chip supply chain resiliency.

The U.S. DOD is responsible for the Chips for America Defense Fund which aims to implement a national network for domestic, university-based prototyping, and lab-to-fabrication transition of semiconductor technologies. This program includes coordination across DOC, the Department of Energy, the Department of Homeland Security, and the Office of the Director of National Intelligence to establish a group of private companies for facilitating the production of secure semiconductors.

The CHIPS Act authorizes $81 billion of new NSF funding over Fiscal Years 2023-2027 to strengthen fundamental research, establish technology innovation partnerships, invest in equitable scientific education, and address research security[9] The Directorate for Technology, Innovation and Partnerships (TIP) created by NSF is tasked with supporting early-stage research that advances advanced computing and communications capabilities and infrastructure critical to national security and economic competitiveness.

The DOC is responsible for a majority of tasks in the CHIPS for America Act including manufacturing incentives, public wireless supply chain innovation, and R&D. The main DOC responsibilities fall under the R&D section of the bill which includes responsibilities for the National Semiconductor Technology Center[10], a National Advanced Packaging Manufacturing Program, a Manufacturing USA Semiconductor Institute, and Microelectronics Metrology R&D. These programs help involve industry in the manufacturing prototype process and research virtualization of semiconductor machinery, strengthen advanced assembly, test, and packaging capabilities, and advance measurement science, standards, material characterization, instrumentation, testing, and manufacturing capabilities.

The CHIPS Act tasks NIST with addressing a multitude of strategic goals including financial, information security, workforce development, equitable small business opportunity, and financial accountability. These goals look to increase capital and resources from the semiconductor private industry and encourage collaboration between industry, investors, customers, designers, and international firms. This collaboration and financial backing will build a secure and resilient semiconductor supply chain that follows the standards and guidelines on information security, data tracking, and verification.

---

[8] CHIPS and Science Act 2022 Division Summary, 2022, Senator Chris Van Hollen, https://www.vanhollen.senate.gov/download/chips-and-science-act-of-2022-summary&download=1

[9] NSF (2023) CHIPS and Science. Retrieved from https://new.nsf.gov/chips

[10] NIST (2023) A Vision and Strategy for the National Semiconductor Technology Center. (U.S. Department of Commerce, Washington, D.C.), Available at: https://www.nist.gov/document/vision-and-strategy-national-semiconductor-technology-center

## Equity and Workforce Development

By prioritizing digital equity and workforce development, the R&D community can expand access to the benefits of NextG communications technology and deliver meaningful communications products, services, and research opportunities to traditionally underserved communities. Various federal R&D initiatives seek to bridge the digital divide and ensure equal access to reliable, high-performance communications networks that increase opportunities for education and commerce, as well as improve quality of life.

Recent legislation recognizes the importance of equity and workforce development in the NextG communications industry. As part of the American Rescue Plan Act of 2021[11] funding for the National Telecommunications and Information Administration (NTIA) includes $2.75 billion to support broadband infrastructure deployment and digital inclusion initiatives. This funding is to help close the digital divide by providing access to high-speed internet in underserved communities and supporting digital literacy and skills development.

The CHIPS for America Act also recognizes the importance of workforce development in the NextG communications industry. This act provides $52 billion in funding for semiconductor manufacturing and R&D, with a portion of this funding going toward workforce development initiatives. The act includes provisions to support the training and development of a highly skilled workforce in the semiconductor industry, with a focus on increasing diversity and equity in the workforce.

In addition to these workforce development programs, it is also important to prioritize equity in the design and development of NextG wireless communications products and services. This includes considering the needs of underserved communities in the design and development process and ensuring that products and services are accessible and affordable for everyone. Providing affordable, reliable, and high-speed internet is crucial in bridging the digital divide and ensuring that underserved communities have access to the same opportunities as those in more affluent areas. Broadband coverage, reliable connectivity, and high data rates provided by NextG networks will enable better and more connectivity of people and devices to the internet, particularly in rural and remote areas. High data rates and low latency are essential for real-time applications such as telemedicine, distance learning, and remote work to function effectively. Energy efficiency is crucial in addressing the lack of reliable access to electricity across a segment of rural and underserved communities. Incorporating advanced security and privacy features into NextG networks can address concerns about data security, particularly for those who are hesitant to use digital services or public utilities. Open architecture for NextG networks can foster competition and innovation and reduce barriers to entry for new communications hardware and service providers, leading to lower prices, better service for consumers, and new economic opportunities currently unavailable to underserved communities. Equitable design and development of future communications products and services, training opportunities, and economic development opportunities can help provide all Americans with the skills, knowledge, and access needed to participate in this rapidly growing industry.

[11] "Text - H.R.1319 - 117th Congress (2021-2022): American Rescue Plan Act of 2021." Congress.gov, Library of Congress, 11 March 2021, https://www.congress.gov/bill/117th-congress/house-bill/1319/text.

## Expanding R&D Partnerships

New types of R&D partnerships between industry, government research agencies, and academia continue to drive communications system innovation. Examples of such partnerships sponsored by NSF and NIST include Wireless Spectrum Research & Development WSRD[12]; and the Resilient and Intelligent NextG Systems (RINGS) Grant Program.[13] NSF sponsored partnerships include Technology, Innovation, and Partnerships[14]; Future of Semiconductors[15], AI Institute for Future Edge Networks and Distributed Networks (AI Edge)[16] ; Spectrum Innovation Initiative[17] ; Platforms for Advanced Wireless Research (PAWR)[18] ; and NSF/Intel Partnership on Machine Learning for Wireless Networking Systems (MLWiNS).[19] NIST sponsored partnerships including the National Semiconductor Technology Center, the National Advanced Packaging Manufacturing Program, NIST Generative AI Public Working Group [20], and the NextG Channel Model Alliance. [21]

R&D organizations need to demonstrate the engineering feasibility of new communications technologies and coordinate with standards development bodies to ensure that fundamental research aligns with future standards specifications. Private industry needs to maintain awareness of outputs from R&D organizations and standards bodies to inform business decisions to develop and commercialize products and services against these standards that meet consumer demand. Therefore, organizations across the entire communications R&D landscape are presented with incentives to work together to advance emerging NextG technologies, standards, and partnership models.

## The Role of Standards Development

In order to transform communications systems rather than incrementally advance current capabilities, NIST Working Group participants encouraged the R&D community to envision long-term engineering solutions independent of standards development cycles. While new network generations are typically introduced every 10 years, technology innovation often takes place independently of this cycle. Continuous innovation outcomes affect what is included in each generation's standard release and what new capabilities are built following a standard's release. Thus, some of the technologies discussed in this report may not be sufficiently mature to specify in sixth-generation standardization activities (6G) expected within the next eight-ten years. However, it remains critical for the R&D community to continue work to advance these capabilities and support high-risk, high-reward experimentation.

[12] NIST (2023) Wireless Spectrum Research & Development (WSRD) https://www.nist.gov/news-events/events/2023/05/wsrd-workshop-making-data-available-national-spectrum-management
[13] NSF (2021) Resilient Intelligent Next Generation Systems. Retrieved from https://www.nsf.gov/pubs/2021/nsf21581/nsf21581.htm
[14] NSF (2022) Technology, Innovation, and Partnerships.Retrieved from https://beta.nsf.gov/tip/latest
[15] NSF (2022) Future of Semiconductors https://beta.nsf.gov/funding/opportunities/national-science-foundation-future-semiconductors
[16] NSF (2023) AI Institute for Future Edge Networks and Distributed Networks (AI Edge) https://live-aiedge-program.pantheonsite.io/
[17] NSF (2023) Spectrum Innovation Initiative. Retrieved from https://www.nsf.gov/mps/oma/spectrum_innovation_initiative.jsp
[18] NSF (2023) Platforms for Advanced Wireless Research (PAWR) https://advancedwireless.org/
[19] NSF/Intel (2019) Partnership on Machine Learning for Wireless Networking Systems (MLWiNS) https://www.nsf.gov/pubs/2019/nsf19591/nsf19591.htm
[20] NIST (2023) NIST Generative AI Public Working Group. Retrieved from https://www.nist.gov/news-events/news/2023/06/biden-harris-administration-announces-new-nist-public-working-group-ai
[21] NIST (2023) NextG Channel Model Alliance. Retrieved from https://nextg.nist.gov/

# NextG Communications Standards Cycle

The purpose and adoption of previous standards generations follow a similar pattern and may shed light on what to expect as the industry transitions from 5G commercialization to NextG capabilities. During the Joint Communications and Sensing working group panel discussion that NIST facilitated on June 29, 2022, stakeholders noted that every two standards generations present similar technical goals that begin by delivering increased capabilities to business applications in the first generation before impacting the wider consumer electronics market in the second generation. [22] Odd generations normally introduce new wireless communications approaches for commercial applications and business users, and even generations apply these capabilities for more widespread, general consumers. For example, first-generation wireless (1G) introduced voice communications to large commercial organizations and second-generation wireless (2G) commodified those capabilities for public users. Third-generation (3G) and fourth-generation wireless (4G) standard releases delivered mobile broadband services following a similar pattern. Working Group participants recognized this development cycle and expect that future generation networks beginning with 6G will likely scale access to 5G capabilities such as tactile internet, mobile robotics, or remote control of real and virtual objects through cyber-physical systems currently reserved for niche applications. Scaled proliferation of data-intensive consumer devices expected during NextG commercialization will require the R&D community to introduce new standards and technologies related to spectrum management, interference mitigation, and data privacy to overcome the communications challenges described in this report.

[22] NIST (06/29/2022) NextG Wireless R&D Gap Analysis Workshop, Joint Communications and Sensing (U.S. Department of Commerce, Washington, D.C.)

## Organization of this Report

This report identifies critical-path communications R&D gaps over a long-term time horizon that are of interest to a diverse stakeholder audience. Although NIST convened the stakeholder Working Group that identified and described the gaps included in this report, the challenges facing the telecommunications and computing industry are too broad for a single federal or commercial entity to address independently. As a result, NIST organized this report into several themes so that readers may focus on the specific technical section(s) that align most closely with their research areas of interest.

The following sections describe high-priority technology research gaps that, if addressed, will help R&D organizations meet goals such as:

- Increase the automation, energy efficiency, and cost efficiency of domestic manufacturing processes to reduce schedule and price variability risks associated with overseas hardware development.
- Provide hardware manufacturers with new chipset designs, materials, and production methods to meet the performance requirements expected of NextG systems.
- Equip products and services supporting non-traditional NextG applications related to healthcare, transportation, public utilities, education, and personalized customer experiences with high bandwidth, low-latency, and secure communications capabilities.
- Develop new standards and testing approaches to evaluate the performance and quality of experience of new devices, networks, and applications supporting NextG systems.
- Expand digital equity for underserved communities by increasing the geographic coverage, reliability, affordability, and workforce supporting NextG technology systems and applications.

# Hardware and Higher Frequency Research

NextG hardware components such as tunable filters, terahertz (THz) transceivers, power-efficient devices, cost-effective integrated circuit solutions, and practical phased arrays represent major challenges in the development of NextG systems. In addition, significantly increased demand for wireless communications data and services requires NextG systems to integrate technologies that leverage higher frequency spectrum with existing technologies to deliver networks with greater capacity and coverage. This combination delivers post-5G connectivity, speed, latency, and reliability expectations. [23]

There is a need for new hardware design to overcome challenges associated with transmitting, processing, and receiving communications signals operating in the mmWave, THz, and other higher frequency spectrum. Challenges such as managing interference, overcoming limited range, significant fading, and blockage will require new channel measurement and modeling techniques to understand how signal propagation behaves in future network environments and use cases. Current programs addressing some of these challenges include the NextG Channel Model Alliance, a NIST-led international research consortium focused on the measurement, analysis, and statistical representation of mmWave and THz propagation channels; and the Joint University Microelectronics Program 2.0 (JUMP 2.0). [24] The JUMP 2.0 program is a joint effort between the Defense Advanced Research Projects Agency (DARPA), the Semiconductor Research Corporation (SRC), and a collection of private companies in the semiconductor industry. JUMP 2.0 addresses a myriad of issues on NextG technology and aims to spur innovation in analog hardware.

[23] NIST (05/04/2022) NextG Wireless R&D Gap Analysis Workshop, Hardware and Higher Frequencies (U.S. Department of Commerce, Washington, D.C.)

[24] Semiconductor Research Corporation (SRC). Joint University Microelectronics Program (JUMP). Retrieved from https://www.src.org/program/jump2/

## Hardware

Working Group participants identified several long-term communications hardware gaps related to incorporating new antenna designs, and advanced semiconductor circuits and materials into NextG radio architectures. NextG communications hardware should offer higher bandwidth by considering new substances and materials that can use reflective or analytical properties to overcome the path loss, directionality, and propagation challenges associated with mmWave and THz spectrum. These new semiconductor designs, including materials such as graphene, Gallium Selenide (GaSe), and Silicon Germanium (SiGe), need further development, testing, and extensive supply chain coordination before they are deployed to communications and non-communications use cases at scale.

Accurate and traceable models to characterize the signal propagation and circuit design are needed to accelerate the development and fabrication of NextG semiconductors. In addition, engineering improvements related to beam steering, interference mitigation, redundant transmit and receive components, and updated protocols are needed to allow disparate network endpoints to operate seamlessly.

Large Intelligent Surfaces (LIS) may lead to the emergence of new NextG wireless physical platforms, offering beam steering and analytical computing capabilities, that are more seamlessly integrated into radio hardware and chipsets. In addition, intelligent surfaces present the opportunity to improve spectral efficiency by adjusting the behavior of NextG waveforms through data analytics and signal reflection to overcome propagation loss. Given the rapid proliferation of user and network devices expected for NextG communications systems, future hardware components also need to demonstrate more efficient power consumption than currently used in existing radio design.

### Component and Antenna Design

1. **Need to develop inexpensive, small, higher-quality RF filters that are frequency tunable:** Despite recent advances in signal-processing techniques, it remains difficult to implement software-defined, high-power, and frequency-selective devices.

2. **Need to develop antenna components with new materials that are optimized for NextG requirements:** Working Group participants noted that R&D organizations need to develop large antenna arrays with an increased number of transceiver chains that take advantage of new semiconductor materials and compounds besides traditional silicon. New materials such as graphene, and SiGe, in addition to those used in plasmonic nano-antennas and reflective and/or programmable surfaces, can be integrated into next-generation device, circuit, and systems research to increase the effectiveness of network resource management and support faster, automated control.

3. **Need to develop new antenna architectures:** Working Group participants noted that researchers need to discover an optimal antenna array architecture that can effectively process outgoing and incoming signals over a broad frequency range within a reasonable form and cost factor. This new architecture will be essential to the widespread commercial adoption of technologies such as Massive Multiple Input Multiple Output (MIMO) and ultra-wideband antennas and their integration into traditional radio frequency circuits.

4. **Need to achieve greater control and flexibility of antenna elements and leverage higher frequency spectrum:** NextG antennas require variable radiation parameters, such as beam width, radiation patterns, and directionality. Antenna designs will need to use these variations (in terms of beam width and beam steering) in order to maximize network capacity and reduce interference. Higher frequencies offer wider bandwidths that are critical for data-intensive NextG applications. Mixed signal technologies, Analog Digital Converters (ADC), and Digital to Analog Converters (DAC) will be stressed to handle NextG data, especially when movement exists between radio and baseband hardware units. Hardware elements, ranging from radio architecture (analog, hybrid, and digital radio front-end units) to amplifiers, need to be revisited to account for radio characteristics unique to higher frequencies in order to take advantage of the higher bandwidth they offer.

5. **Need to increase the cost- and power-efficiency of NextG antenna arrays:** Developing new antennas is difficult and costly, and the ability to rapidly develop cost-effective, power-efficient mobile antenna arrays represents a significant engineering gap going forward. Additional R&D is needed in order to overcome combining the baseband and the antennas for mobile arrays while satisfying the size, complexity and cost constraints.

6. **Need for antenna directional control capabilities:** Working Group participants noted the ongoing need to improve the directionality of large antennas. This need is especially acute for controlling single directions at a time due to blockage challenges inherent in the short wavelengths found at higher frequencies. Possible research topics that could support this need include:

    - Using new lenses or beamforming techniques with different coefficients may support more granular control over antenna directionality.

    - Developing analog front-end technologies that enable higher frequencies, higher power, more controllable hardware elements, and larger bandwidth than existing radio components. The R&D community can combine analog front-end components with digital back-ends to result in faster data converters and higher resolution.

### Large Intelligent Surfaces (LIS)

7. **Need to develop tunable LIS:** An artificial surface made of electromagnetic materials, LIS can change the propagation of incoming and outgoing radio waves. Both passive and more advanced LIS should be considered. LIS acting as reconfigurable reflectors with passive elements have the advantage of low power consumption since they only reflect the signals passively without involving active RF chains. By properly tuning the phase shift via a LIS controller, the reflected signal can be superimposed constructively at the targeted receiver. This both boosts the received signal power while suppressing the reflected signal at the targeted receiver to reduce co-channel interference. To accomplish some of these goals, the material selection and the development of traceable models for LIS, models to characterize the channel, and the CSI are important, especially in the THz band.

8. **Need to develop LIS solutions that improve signal processing efficiency and power consumption requirements expected for larger RF chains:** Spectral efficiency, one of the key requirements of NextG, can be achieved by a high spatial multiplexing gain from massive MIMO.

However, connecting several RF chains will lead to overcomplicated signal processing, extremely high power consumption, and prohibitive hardware cost. LIS are promising energy-efficient and cost-effective solution for tackling the above challenges. It is envisioned that an initial leap from traditional massive MIMO toward LISs can provide LIS-assisted smart radio environments and generate a completely new network paradigm for NextG networks.

9. **Need to collect and utilize meta-surface sensing data to optimize NextG network performance:** In order to materialize the concept of a smart radio environment, researchers must address challenges related to the configuration and optimization of the environment according to the network conditions.This problem persists in the massive amount of sensing data collected on the meta-surface and the amount of feedback for the overall network controller. Effective solutions need to be developed to reduce the amount of sensing data required for network optimization, e.g., only enough information necessary for optimized performance is to be provided to network controllers with low overhead and high energy efficiency.

### New Radio Interface System Design

10. **Need to redesign NextG radio front-end components to process higher frequency spectrum more cost- and power-efficiently:** New systems optimized for high frequency communications may redesign radio front ends to include multiband networks that balance tradeoffs between packaging, heat distribution, and cost constraints. This could include widespread distribution of small cell networks that demonstrate performance benefits that warrant the cost and technical complexity of installation. Working Group participants identified additional priority innovations related to radio hardware component design that include:

    - Need to design transceivers that possess full duplex transmission.
    - Need medium access controls that simultaneously manage radar packets and communication packets.
    - Need to develop packet protocol technologies and appropriate design of control signaling/information for joint radar and communication functions. This allows communication to start from medium access, to passive access, and end at active radar access.
    - Need to improve the design of antennas, radio frequency interfaces, analog-digital converters, and signal processing functions to enable joint communications and sensing applications.
    - Need to improve the coverage of programmable hardware with flexible front ends that span 6-20 GHz, which the Federal Communication Commission (FCC) has designated as the next frontier.

11. **Need for programming large reflector rays for beam deployment:** There is a programming need for massive reflectarrays in order to change beam deployment. A newly defined codebook will help steer massive reflector rays and change the way experiments are done. Therefore there is a research gap at the intersection of electromagnetics, communications, and signal processing.

### Radio Integration from Semiconductors and Scalable Radio Architectures

12. **Need to develop more power-efficient semiconductor chipsets to support larger-scale antenna arrays:** Due to the increased data rate, bandwidth, number of beams, and higher order modulation required of NextG, advanced communications systems should overcome unreasonable power consumption by using redesigned, lower-power semiconductor chipsets.

> This architecture will serve extremely large-scale arrays with tiny antennas for mobility. New advancements in radio architecture, signal processing, and building large apertures with low-power base stations represent complex challenges this will require system-level optimization of algorithms and hardware. Spectrum sharing awareness at the device level is not available, and therefore understanding the environment around the base station is crucial.

### Interdisciplinary R&D Techniques

13. **Need to emphasize interdisciplinary research across optical, quantum, communications, signal processing, and networking fields:** More diverse research collaboration represents a near-term activity that would help facilitate longer-term hardware and higher frequency innovation. Engaging with disciplines adjacent to the communications industry such as radar/sensing, consumer electronics, aerospace, defense, automotive, and energy may also produce new ideas on how to integrate new hardware technologies into networking systems.

## Higher Frequency Research

High-frequency bandwidth such as mmWave and THz presents a unique opportunity to deliver the increased bandwidth and minimized latency required for NextG products and services. mmWave refers to the portion of the electromagnetic spectrum that includes frequencies between 30 and 300 GHz. THz bands, on the other hand, refer to frequencies between 0.1 and 10 THz, which are higher than mmWaves. NextG systems that seek to leverage the increased bandwidth offered at high frequencies must overcome challenges related to propagation, signal blockage, small-cell deployment, and electromagnetic radiation associated with mmWave and THz spectrum. Frequency-dependent and ultrawideband channel modeling: determine the dependence of key channel parameters, such as delay spread, on the carrier frequency above 100 GHz, establish measurement-based channel statistics, and analyze the impact of the very large bandwidths possible in the >100 GHz spectrum.

### Channel Propagation

14. **Near Field Channel Modeling:** Since NextG receiving antennas may interact with the transmitting antenna via capacitive or inductive coupling in the near-field, special measurement equipment and strategies for modeling are needed.

### Deployment

15. **Need to overcome form factor, energy consumption, cost, and processing constraints associated with mmWave deployments:** Deployment at mmWave has challenges but delivers significantly increased bandwidth. THz spectrum presents additional challenges related to communication use cases but with many benefits for spectroscopy, imaging, and sensing.

- Research organizations need to determine the economic viability of NextG applications dependent on high-frequency bandwidth, such as indoor extended reality technologies, that may be hindered by heat generation issues, processing power and storage limitations, and form factor constraints.

- Outdoor applications require higher bandwidth and lower latency, which requires new infrastructure that can push processing to the edge. For example, Working Group participants noted the need for R&D organizations to more clearly define technical requirements and engineering approaches supporting mmWave-dependent extended reality applications such as handset automation and vehicle-to-vehicle communications before these deployments become technically or economically viable in outdoor environments.

### Blockage

16. **Small Cell Endpoint and Antenna Adoption:** NextG communications systems researchers may consider overcoming blockage challenges at higher frequencies through more widespread adoption of small cell endpoints and increased application of small antennas on Radio Unit (RU) network chips or Internet of Things (IoT) sensors. This may represent an incremental advancement in network decentralization concepts the R&D community began investigating in the lead-up to 5G. Overcoming blockage challenges may require large reflective surfaces and improved near-field channel modeling to ensure small cells seamlessly integrate with existing deployment architecture.

17. **Development of Large Reflective Structures and Intelligent Programmable Antennas:** In order to overcome blockage challenges associated with mmWave and THz propagation, these structures should have characteristics like reflect-arrays or metasurfaces. These characteristics, however, would require larger antenna arrays with increased transceiver chains at higher frequencies.

### Waveform Development

18. **Need to design future generation wavefront and waveform engineering approaches to better support near-field and far-field network applications:** With larger structures, the field becomes farther away. An anecdote to this problem could be using lenses or beamforming with different coefficients to more effectively focus in the near field. Beam-focusing with programmable arrays, as opposed to regular beamforming, could also shift focus to near-field waveform engineering. Near-field applications could use Bessel beams that self-heal and propagate another signal if the wavelength is blocked more than 50%. Airy beams that self-bend to overcome obstacles represent another new type of beam that may work well at higher frequencies in the far field with the support of intelligent, reflective surfaces.

    Researchers may also pursue new ways to control the properties of an electromagnetic wave. Orbital angular momentum (OAM) modes for THz may reduce communications systems' reliance on digital signal processing when controlling channels. At these smaller submillimeter wavelengths, researchers can use small structures.

19. **Need to design new waveforms that are tailored to specific use cases and propagation environments:** Working Group participants noted that the R&D community should also emphasize the development of new waveforms and wavelengths specifically designed for indoor, outdoor, and possibly non-terrestrial space networks (ie. satellite constellations) at higher frequencies.

    - Joint ultra-broad wavefront and waveform engineering may improve next-generation applications. Currently, these NextG applications do not rely upon a physical network core, but instead are comprised of a collection of computational resources shared by many networks systems, such as nanonetworks and space networks

    - Efficient signal amplification and modulation is needed at higher frequencies. Multi-carrier or single-carrier waveforms may constitute an alternative to Orthogonal Frequency-Division Multiplexing (OFDM) depending on the use cases.

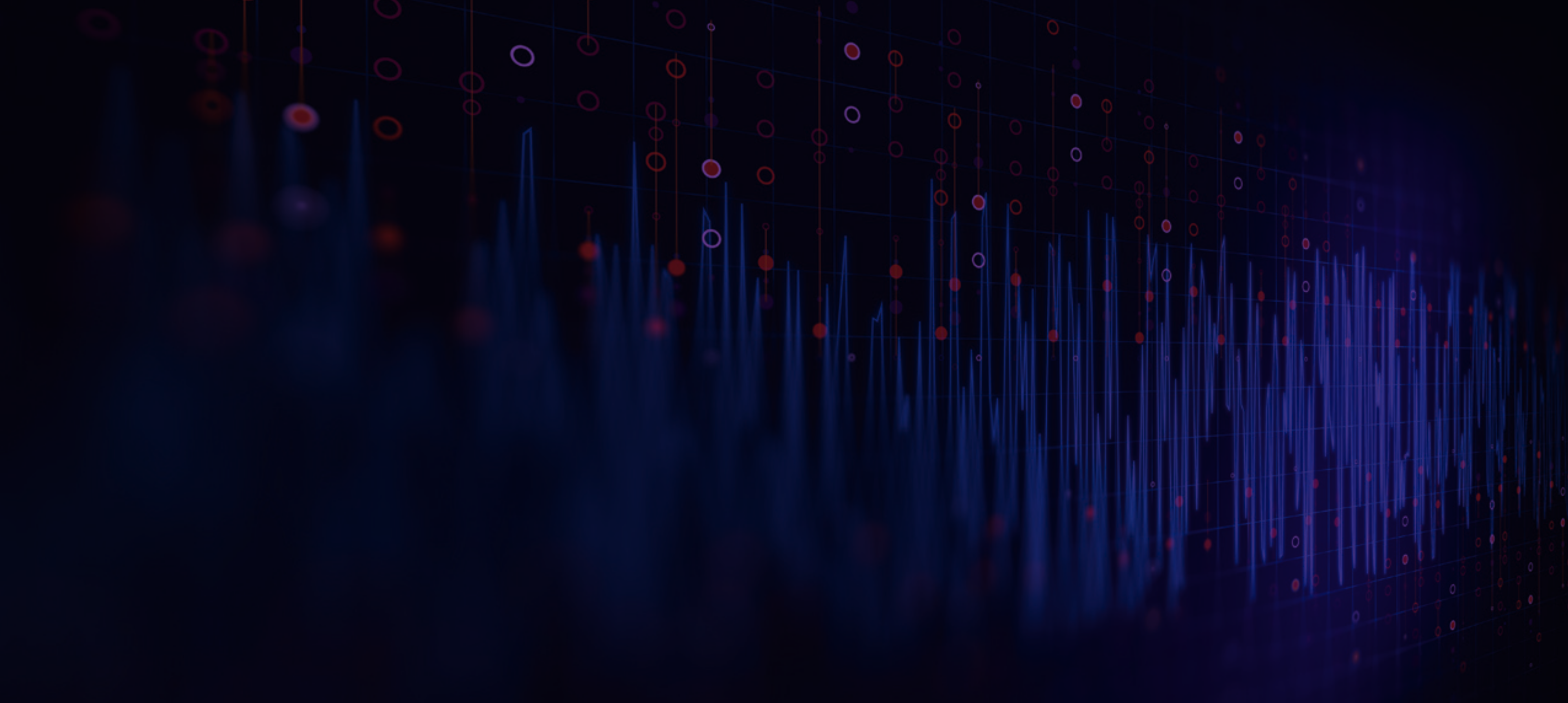
## Bessel Beams

20. **Need to increase research on Bessel Beams:** Research for Bessel beams has mostly relied on utilizing lenses like axicons which limits them to stationary deployments. Therefore, this is an opportunity for researchers building rays and for the researchers building NextG systems. Bessel beams and MIMO are not new, but researchers need to make use of them with communications tools that have advanced since Bessel beams and MIMO concepts were first introduced.

## Terahertz (THz) Applications

21. **Use Cases:** Working Group participants identified several opportunities for the R&D community to overcome the form factor and deployment constraints associated with placing more antenna elements on a greater number of endpoints. Participants did not think it was feasible to place hundreds or thousands of antennas on existing terrestrial network infrastructure, such as traditional cell towers, to support mmWave or THz use cases. Therefore, researchers need to determine how to integrate new small cell endpoints with existing communications networks. Participants also noted that higher frequency applications, such as augmented reality headsets, could be supported indoors with an antenna-covered ceiling.

Satellite network operators are exploring how the narrow beams of THz bands can expand backhaul link capacity to serve fixed and mobile networks. The R&D community should further explore how satellite and terrestrial systems can co-exist in close physical proximity due to the high-gain, narrow propagation characteristics of THz spectrum. This would likely not work with traditional cell towers and would require small cell providers to interface with today's operator-driven outdoor cell-based systems. The R&D community may need to consider how local, private, and/or small cell network providers could coexist with existing cellular infrastructure in a mutually beneficial way to facilitate the use of the THz spectrum.



# Spectrum Science and Sharing

As NextG communications and computing use cases become increasingly integrated and sophisticated, the amount of data to be gathered and transmitted between users, machines, and applications will exponentially increase the demand for radio spectrum usage. In order to leverage wireless spectrum to deliver the higher speed and data rates required for NextG applications, communications researchers must develop new methods of sharing spectrum between diverse end-uses and managing spectrum more efficiently. Meanwhile, they must also accommodate form factor limitations on antenna size and power efficiency needed to provide wireless services at a reasonable cost and level of complexity.

The increased demands on cellular traffic in terms of range, throughput, and latency require the use of frequency bands that combine the favorable propagation characteristics of low-band frequencies (< 1 GHz) with the wider bandwidths available in the high-band (> 24 GHz). This has led to increasing swathes of mid-band frequencies being allocated for 5G services. In the United States, the four most recent allocations in the mid-band are the 2.5 GHz band (2.496 – 2.690 GHz), the 3.7 - 3.98 GHz band (C-band), the immediately adjacent 3.55 - 3.7 GHz band (Citizens Broadband Radio Services, or CBRS) and the latest allocation of 3.45 - 3.55 GHz for cellular services. In addition, the 6 GHz band (5.925 – 7.125 GHz) has been allocated for unlicensed use.

Prior to reallocation, each of the above bands already had incumbents which either needed to be relocated, as was the case with satellite incumbents in C-band, or mechanisms for sharing and protecting incumbents needed to be developed as in CBRS and 6 GHz. It is becoming increasingly clear that the demand for mid-band spectrum for future wireless systems will require spectrum sharing between new entrants and incumbents, many of which are federal systems, e.g., in the 3.1 – 3.45 GHz and 7 – 8 GHz bands. The FCC recently issued a Report and Order on the 12.2 – 12.7 GHz band reinforcing protections for satellite systems and rejecting terrestrial mobile uses. The FCC also issued a Notice of Proposed Rulemaking on the 12.7 – 13.25 GHz band, proposing sharing the band between terrestrial mobile systems and commercial and federal incumbents.[25]

In addition to co-channel incumbents, adjacent channel interference scenarios also need to be considered. The recent dispute over 5G and radar altimeters is an example of the potential for adjacent channel interference unless sharing studies and research are conducted well in advance of spectrum reallocations. The FCC's Receiver Standards NOI [26] also considers how wireless receivers can be improved to facilitate better sharing between both co-channel and adjacent channel incumbents.

The FCC's Technological Advisory Council (TAC) recently published recommendations for future spectrum sharing based on lessons learned from the sharing scenario developed for CBRS. Sharing in CBRS is facilitated by a Spectrum Access System (SAS) and an Environmental Sensing Capability (ESC) that detects the presence of the primary incumbent, Navy radars. [27] However, the new bands are considered to have different incumbents, like airborne radars, that cannot be protected using databases and passive users like Earth Exploration Satellites (EES) satellites. Hence, NextG research needs to develop new methodologies that will improve the operation of cellular and other wireless systems in the shared spectrum. This section identifies several priority technology gaps that, if addressed, would enable NextG networks to more effectively meet disparate data, reliability, and coverage requirements across an expanding set of wireless spectrum stakeholders.

22. **Improved propagation models focused on interference rather than coverage:** Spectrum can be shared geographically, temporally, or between users to increase spectrum access to wireless consumers and providers. Spectrum-sharing techniques rely on spectrum occupancy measurements that are typically used to determine whether new transmitters can be added without causing additional interference. However, assessing interference remains challenging. Spectrum measurements should differentiate between the various communications and non-communications sources of interference, including intentional radiators, man-made noise, natural noise, and intermodulation spurs.

    Most existing propagation models focus on quantifying the coverage of the system under consideration. While such efforts need to continue, especially in the new frequency bands between 7 – 24 GHz, there needs to be an increased emphasis on developing interference models. Working Group participants indicated that the propagation models used to determine interference in CBRS are overly conservative leading to reduced spectrum utilization. In order to improve sharing, the protection needs of incumbents as well as typical deployment scenarios need to be considered. For example, the CBRS ESC mechanism that was developed for protecting Navy radars will not be suitable for protecting airborne radars in 3.1 – 3.45 GHz or EES in the 12.7 – 13.25 GHz band.

[25] FCC Notice of Inquiry and Order, "Expanding Use of the 12.7-13.25 GHz Band for Mobile Broadband or Other Expanded Use," https://docs.fcc.gov/public/attachments/FCC-22-80A1.pdf , October 28, 2022

[26] FCC Notice of Inquiry, "Promoting Efficient Use of Spectrum through Improved Receiver Interference Immunity Performance," https://docs.fcc.gov/public/attachments/FCC-22-29A1.pdf

[27] FCC Technological Advisory Council (2022) Recommendations to the Federal Communications Commission Based on Lessons Learned from CBRS,"https://www.fcc.gov/sites/default/files/recommendations_to_the_federal_communications_commission_based_on_lessons_learned_from_cbrs.pdf

23. **Improved spatial interference models for Massive MIMO antennas:** Massive MIMO in the mid-bands is a proven technique for 5G and is expected to continue being an integral component of NextG specifications in the 7 – 24 GHz frequency band with even more antenna elements. As with propagation studies, Massive MIMO research has focused mostly on improving the capacity of the system under consideration. However, the spatial degrees of freedom can also be exploited in reducing interference to incumbents in a shared spectrum scenario. Research is needed to develop probabilistic spatial interference models for Massive MIMO which can then be combined with interference propagation models to develop end-to-end interference models for NextG spectrum sharing.

24. **NextG needs to be "sharing native":** Cellular specifications from 1G to 5G have been developed for use in an exclusively licensed spectrum. Recent modifications, such as License Assisted Access and 5G New Radio Unlicensed (5G NR-U) spectrum, enables operation in the unlicensed bands. However, the experience with CBRS has demonstrated that the problems of Time Division Duplex (TDD) cellular systems operating in shared spectrum need the development of new protocols. For example the new protocols would allow deployments in adjacent bands to utilize different uplink/downlink splits without causing mutual interference.

25. **Need to evaluate and develop better spectrum sharing techniques:** Better components, devices, techniques, and algorithms are needed to effectively manage interference between various systems operating in the same bands. More specifically, there is a need to develop inexpensive, small, higher-quality RF filters that are frequency tunable. The RF filter development would enable more users to fit into the spectrum without the added and unnecessary complexity elsewhere in the system. Due to the engineering complexity of processing all frequency components and expanded energy consumption across spectrum sharing systems, high-power transmit filters are potentially more challenging to tune than receiver filters. While good signal-processing techniques are available today, it remains difficult to implement software-defined filters. In addition, more sophisticated transmission power management techniques are also needed to improve spectrum sharing. System-level approaches including both collaborative and non-collaborative approaches need to be developed. When collaboration channels are present, the industry needs to determine the information that should be shared among networks to facilitate efficient coexistence. The DARPA Spectrum Collaboration (SC2) program has supported the development of solutions in this space. Another example is the discussion in the Institute of Electrical and Electronics Engineers (IEEE) 802.11ax task group considering local vs. global optimization in mitigating interference.

    There is a need to develop more integrated spectrum situational awareness, command, and control architecture to enable controllable, adaptive, and flexible operations of hardened spectrum-dependent systems. A promising path forward for improving spectrum sharing is the greater use of adaptive algorithms and machine learning to more efficiently and automatically manage spectrum sharing. Adaptive spectrum-sharing systems that leverage machine learning algorithms will need to operate within very clear rules, stating how to collaborate with new radio systems, share spectrum across systems, and optimize resource utilization. These rules would enable automated spectrum monitoring and enforcement, making networks more resilient to jamming and responsive to security threats. However, the rules guiding machine learning on wireless systems have not yet been defined. The lack of rules and the significant computational requirements associated with wireless machine learning deployments are key barriers preventing more effective, automated spectrum sharing.

26. **Need testbeds and metrics to evaluate spectrum sharing:** There are a number of federally supported testbeds that can be used for evaluating spectrum sharing. The Wireless Spectrum Research and Development (WSRD) Interagency Working Group published a Networking and Information Technology Research and Development (NITRD) report compiling a summary of federally-supported testbeds currently in use across the nation. [28] However, due to technical and cost considerations, federally-supported test beds tend to be specialized to particular radio and radar technologies. Thus, there is a need to develop more general, large-scale testbeds that reflect more realistic scenarios to evaluate coexistence performance. A few projects and initiatives including the NSF's Platforms for Advanced Wireless Research (PAWR) program, [29] the FCC program experimental license, and the DARPA spectrum collaboration challenge may have begun to answer this need. In addition to testbeds, evaluating spectrum sharing requires the use of metrics established to qualify the effectiveness of the so-called coexistence of different systems utilizing the same spectrum. Sharing is more difficult to achieve across heterogeneous or different types of systems and priorities, and the sharing metrics need to account for multiple sharing dimensions, encompassing the system performance across all layers of the networking stack. More specifically, the metrics need to account for what agents operate in a given spectrum band, what types of information exchange they care about, and what priority access they have. While some metrics are technology agnostic and consider overall spectrum efficiency and utilization, there needs to be different metrics that more accurately characterize the sharing as "seen" or experienced by different systems. Metrics considering group versus individual optimization should be considered in addition to the overall throughput and opportunity cost. These evaluation metrics, together with realistic testbed environments, should encourage the evolution toward better spectrum-sharing technologies.

27. **Need to study spectrum management techniques:** Traditional spectrum management focuses on coverage optimization for noise-limited systems with minimal frequency reuse. In mmWave bands, where propagation is greatly affected by small changes in device location, open new opportunities for efficient spectrum management, including between services. In addition, a dense deployment for higher bands is needed to provide a sufficient probability of service in a highly challenging propagation environment. Improved methods of providing reliable service in a shared-spectrum environment are lacking. The Working Group participants identified the potential for a new spectrum management challenge associated with supporting continuous coverage in this new environment. Participants recognized the need to develop a consensus or shared vision of how the spectrum is managed, what types of control (centralized versus distributed), and what operation modes (licensed versus unlicensed) are used. Adequate rules for resolving conflicts resulting from sharing in all of these regimes and operation modes are also needed. Thus designing appropriate SASs for both outdoor and indoor operation covering both licensed and unlicensed bands up to 100 GHz is needed. Commercial systems today are able to detect, characterize, and report system performance impacts due to RF energy incoming from independent spectrum users. This is done via key performance indicators (KPIs). However, KPIs are not designed to indicate the source of interference, only its effect on performance. Once the source of interference can be detected, it enables electromagnetic spectrum dynamic planning,

[28] Networking and Information Technology Research and Development (2022) Advanced Wireless Test Platforms Team Information Request Report https://www.nitrd.gov/pubs/AWTP-Info-Request-Report-2022.pdf
[29] NSF (2023) Platforms for Advanced Wireless Research. Retrieved from https://advancedwireless.org/

directing and controlling, all of which are necessary to conduct real-time spectrum operations in heterogeneous electromagnetic environments. In some cases, terrestrial and satellite systems may not need to utilize the same frequency band, and a “unified” light-licensing framework supported by a common database of fixed deployments could enable rapid self-coordination between co-primary terrestrial and satellite gateway deployments in higher-frequency bands (e.g., the 70/80 GHz band).

# Joint Communications and Sensing

Joint communications and sensing (JCAS) capabilities refer to technologies that support the integration of sensing into communications networks, and the creation of a shared communications system uses common modules to transmit, receive, and analyze signals for both communications and sensing applications. To achieve coexistence between communications and sensing systems, researchers need to advance the underlying hardware capabilities that enable sensor-aided communications such as Massive MIMO antenna arrays and full duplex circuits. Semiconductor chip technologies must also support improved power efficiency, spectrum efficiency, and scale of production. Also, there is a need for the development of new multi-frequency spectrum processing algorithms and suitable channel models that properly characterize the joint communications and radar propagation environment.[30]

In addition, new network architectures need to accommodate a system co-design for both communications and sensing, along with updated standards that integrate sensing data into existing communication systems. Redesigned network architectures and updated standards would improve the management and coordination of the increased spectrum and number of devices available to support NextG joint communications and sensing systems.

### Joint Communications and Sensing Systems

28. **Need to consider updates to existing communications standards to support improved sensing:** Working Group participants discussed the need to clearly define joint communications and sensing architectures. Some argued that the primary motivation for mixing radar and communications activities is logistical efficiency. Because communications infrastructure is already deployed, NextG systems could leverage existing communications hardware for sensing applications with only minor updates to current standards. Sensing has the potential to make communications network operations more efficient and diversify next-generation applications.

[30] NIST (06/292022) NextG Wireless R&D Gap Analysis Workshop, Joint Communications and Sensing (U.S. Department of Commerce, Washington, D.C.)

Others made the case that the R&D community should fundamentally re-architect a joint communications and sensing system (developing a new, differentiated system and protocol co-design), rather than combine available technologies in current network designs. These new co-designed standards would then drive the development of NextG hardware, signal processing techniques, algorithms, and prototypes all optimized for associated joint communications and sensing applications.

29. **Need to design communication channel estimation signals to double as sensing signals:** Channel models developed for network communications need to be updated to more precisely characterize radar systems. Researchers need to validate the channel models used in wireless network research and design, capture the right characteristics relevant to sensing, and further refine those models.

    Algorithms supporting NextG signal transfers will need to assume a certain channel model, and it is not yet determined whether these channel models will describe communications, radio, or joint sensing signal behavior. The Working Group noted that the research community needs to define whether bandwidth requirements for communications applications are sufficient to support radar sensing use cases, and whether joint communications environments will need to leverage two-channel models to characterize communications and radar propagation simultaneously.

30. **Need to increase access to multi-frequency communication to improve sensing resolution:** Access to multiple frequency bands, such as adding sub-THz to low-, mid-, and high-bands, helps sharpen the sensing capability of the entire network. Measurements from multiple bands need to be fused together and leveraged for sensing and for the development of multi-band channel models.

31. **Need to increase performance, fault-tolerance, and automated operations of software implementation of NextG communications functions:** Some Working Group participants expect that over the next 10-20 years, cost and deployment considerations will drive almost exclusively software-based implementations of new communications systems. This trend would require addressing basic questions about the fault-tolerance of software-based networks, and real-time software signal processing. Some aspects of this work are covered in data privacy issues, but there is an overall gap in understanding opportunities to improve the resilience and automation of software-defined communications networks.

32. **Need to develop improved spectrum coordination methods to mitigate interference between digital communications and radar signals:** Radar presents the challenge of being an uncoordinated system that uses receiving devices that do not communicate with one another. This system creates interference and makes it possible for bad actors to jam devices. Therefore the research community needs to significantly improve the coordination of communications and radar devices.

33. **Need to research different innovation opportunities for joint communications and sensing waveforms:** A waveform built for radar has a well-defined structure for known information, while a communications waveform has more entropy for unknown information. Therefore, researchers have more opportunities to innovate with radar due to its known communication waveform. As

an example, in order to improve timing ranging for radar, researchers have been using OFDM form to exploit structures like preamble sequences.

34. **Need to standardize mmWave network deployments:** The R&D community needs to close the conceptual gap of how best to leverage mmWave spectrum at scale. Researchers should investigate what ground-based and space-based system designs and functionalities are available to make massive mmWave commercially viable to support communications and sensing applications.

35. **Need to increase the use of Massive MIMO mmWave arrays:** Participants view mmWave Massive MIMO arrays as impactful, because they may significantly improve spatiotemporal resolution by going to higher carrier frequencies and bandwidth. Also with these improvements, large available bandwidths create better range resolution; high carrier frequency becomes better velocity resolution; and miniaturization of large antenna rays forms better angular resolution.

    - Large mmWave phased arrays could solve fundamental performance tradeoffs between optimizing the field of view versus range of radar transmitters.

    - For communications purposes, waveforms only need particular beam patterns to support a reliable connection. However, radar devices will scan over the whole angular range. Therefore, instead of accurate beams, radar beam patterns spread across a wide area and use an immense amount of power. Researchers need to improve the power efficiency and localization of radar systems.

36. **Need to reduce the size and form factor of radar devices:** Joint communications and sensing capabilities can help decrease the size of NextG devices by replacing radio hardware components with smaller, more spatially-efficient communications hardware. Purely autonomous, small, radar-equipped consumer radar devices will need to use joint communications capabilities to ensure its radar components adhere to the small form factor constraints of the device.

37. **Need to develop deployment strategies for joint communications and radar sensor networks:** Traditionally carriers have deployed network resources based on customer demands. However due to NextG applications such as autonomous vehicles and smart utility grids, joint communications sensing networks will require the deployment of sensors where people do not live. Thus, a better understanding of the business case and requirements related to latency, coverage, and other network performance metrics associated with next-generation joint communications and sensing applications will be needed for wide deployments.

38. **Need to explore increased deployment density of joint communications and radar sensors:** A dense deployment becomes a productive joint communications sensing environment because of the increasing density of sensors and short-range radar systems expected to support NextG use cases. Example applications enabled by dense joint communications and sensing network deployments include compressive scanning techniques supported by a large phased array. This technique provides low-latency but lacks sufficient field of view for arrays.

    - Multi-User MIMO (MU-MIMO) receivers can also be repurposed for wideband spatial processing of radar returns. This availability of wideband direct conversion and baseband processing will open up waveform design beyond chip and analog de-chirping.

> The cost of dense deployments is also a factor in not providing enhanced coverage. This area should be researched through the lens of low-cost hardware and radar.

39. **Need to use sensing information as part of network configuration and tuning, including side information from other sensing systems:** Researchers also need to develop new algorithms and protocols that leverage sensing data and support sensor-aided communication. Sensing data will provide useful information to system users, while also being exploited to enhance the operation, adaptability, and resilience of the network itself. Training algorithms that support inference and actuation and use sensing data as an input will enable more effective real-time interactive cyber-physical services. Using sensing information as part of network configuration and tuning, including side information, data neither from the input or output space of the function, from other sensing systems, presents an opportunity to improve network performance and reliability based on dynamic conditions. However, data governance policies need to be established to navigate tradeoffs between network service and external service.

40. **Integrate analog sensing with digital communications:** Researchers need to advance system and protocol design to integrate analog sensing data into digital communications. As of now, sensing signals do not have descriptors or metadata for processing.Therefore, the R&D community must rely on defined relationships for integration. These systems need to be designed to account for communications and sensing metadata and control information for greater flexibility and compatibility.

41. **Improve timing measures and requirements for JCAS systems:** The R&D community needs to define suitable timing measures and system requirements that can fuse multimodal sensing and communications inputs, and support various real-time interactive services such as the ones envisioned in the metaverse.

42. **Need to improve the characterization of electromagnetic propagation for non-linear wireless communication environments:** Researchers need to improve how non-linear environments can modify electromagnetic radiation to facilitate sensing processing. Doppler cloaks and intentional fingerprinting represent two applications enabled by this electromagnetic manipulation.

43. **Need Higher Accuracy for Localization:** NextG radio systems using multiple transmit and receive antennas are able to more accurately estimate the position and orientation of other devices, scatterers, and signal obstacles or reflectors in the environment. Researchers need to develop new methods of utilizing more precise user and/or device positioning and mobility data produced by mmWave antenna arrays to support NextG mapping and navigation applications, as well as updated channel models that account for both communications and sensing signal propagation.

> Researchers need to develop low-complexity algorithms for high-accuracy joint localization and communication at high frequencies.

- Researchers need to more accurately model the first multipath component.

### Joint Communications and Sensing Applications

Working Group participants noted that the R&D community needs to define next-generation applications enabled by joint communications and sensing to justify investments required to re-design or update existing standards and architectures. Stakeholders identified the following applications as being enabled by joint communications and sensing capabilities.

44. **Utilize sensing data to improve augmented reality, virtual reality, and metaverse interactions:** Sensing data could help improve virtual-reality spaces in which users can interact with a computer-generated environment and other users.

45. **Utilize sensing data to improve localization, object recognition, and object avoidance:** Sensing enables more precise localization, mapping, object detection, and avoidance, which are needed to support many NextG applications like autonomous vehicles and industrial factories. The future proliferation of multiple autonomous devices per person will demand significantly more radar spectrum. Accurate localization of user devices may also introduce privacy and security concerns that lead to low trust amongst users.

46. **Utilize sensing data to improve network configuration, management, and resource optimization:** Sensing data could be used to improve communications system reliability, connectivity, and performance by fusing analog and digital signal propagation data. This data provides the JCAS system greater contextual awareness of its surrounding RF environment and connected devices.

# Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning (ML) algorithms and hardware are available in many mobile platforms today. They not only affect resource optimization and the way network resources are managed and self-optimized in relation to shifting traffic and demand patterns. Working Group participants expect NextG systems will require native AI/ML capabilities to process an increasing number of complex data transactions taking place across different components of the network. At the time of publication of this report, most AI processing continues to be done in the cloud. However, NextG communications networks should leverage onboard AI acceleration hardware to allow for higher accuracy, lower latency, and lower power consumption. In addition to hardware acceleration, the communications R&D community can also optimize analytical models for computing efficiency and create algorithms capable of running locally. The Working Group participants also emphasized the need to expand access to properly labeled training data and developer tool sets for advanced communications use cases. Improved AI/ML methods may also enhance wireless system performance, management, and operation.

An AI-native network prioritizes artificial intelligence and computing at the forefront of its architecture and enables intelligence across various network aspects. An AI-native network processes and analyzes data at the base station, edge, cloud, and device levels to inform better decisions on resource management, access control, multi-layer communications, and application performance. Widespread integration of AI decision making algorithms across all layers of a NextG communications network will enable each network node to determine the correct course of action based on defined rules, data intake, real-time application requirements, and network conditions. New algorithms, training data sets, power-efficient data training schemes, and data sharing protocols will enable NextG networks to continuously improve user experiences and adapt network operations based on dynamic environmental conditions, network performance, and application demands. Also, AI/ML capabilities may assess the power requirements of different devices and the energy available to a network to allocate limited resources in a more impactful, efficient manner. Leveraging AI/ML capabilities in NextG systems requires the R&D community to develop new data processing techniques, new system architecture designs, and more energy-efficient computing processes.

47. **Need to equip single and multiple processing blocks with machine learning capabilities to support an AI-native air interface:** ML needs to be used in processing blocks primarily in the receiver. The deployment of these receivers will encounter problems such as data acquisition, model updates, online training, and hardware accelerator integration with the physical layer processing flow. After the initial phase, ML blocks will begin to take over joint channel estimation, equalization, and demapping. ML blocks will become cost-effective and allow for unrealized benefits once the network becomes AI-native.  .

48. **Need to enhance AI/ML computations over resource-constrained and dynamically varying wireless networks:** In order to have a massive number of connected devices in the network layer, there needs to be a solution for understanding the computational power required to collect and process data for these devices. As current network systems present a universal configuration for all AI algorithms, it does not differentiate power requirements based on the varying complexity of algorithms used across communications systems.

49. **Need for better AI algorithms:** AI algorithms will help produce better data insights that can improve network operations, applications, and performance. Data replication and processing at the edge presents opportunities for better equation modeling. This improved modeling can equate to faster delivery of products and services across advanced communications networks. The self-learning and adaptive algorithms will create better networks by constantly updating themselves. In addition, there is a need for AI algorithms to be more trustworthy: secure, robust, fair, explainable, and privacy preserving. Combining these attributes with traditional goals of communication, compute, and energy efficiency is an important research objective to consider.

# Data Availability, Use, and Privacy

It is evident that the exponential generation of data that must be moved, stored, processed, and secured is unprecedented. In just two years, the total monthly mobile data has doubled, reaching 108 Exabytes (EB) per month. [31] The trend continues with more data generated by applications such as video, extended reality (XR), virtual reality (VR), and sensors. While the data storage challenge is significant, the burden placed on the communications infrastructure has never been greater. It is best summarized by the following observation: "It is currently possible to transmit all the world's stored data in less than one year, however, it will require at least 20 years for the transmission in 2040."[32]

While many reports have addressed the storage and communications infrastructure needs and challenges associated with exponential increases of source data, data processing techniques and analytical outputs, this contribution highlights the gaps related to data availability, ownership, management, and use across NextG networks, systems, and devices. The use of data in NextG is tremendously important to most applications and specifically to the NextG system's operation and management. Data in NextG systems represents a valuable commodity, as many configuration and parameter optimization problems using AI and ML have come to rely on proprietary or otherwise sensitive data for solutions.

The R&D and policy communities must clarify the fundamental rights, responsibilities, and technologies necessary to safeguard data privacy across NextG use cases and applications. Organizations must think through the best ways to protect data while making it available for use.[33] Strategies for handling the heterogeneity and the data structure and the data's relevance to various problems and domains need to be developed. Data governance models need to be updated for

[31] Ericsson (2022) "Ericsson Mobility Report" https://www.ericsson.com/4ae28d/assets/local/reports-papers/mobility-report/documents/2022/ericsson-mobility-report-november-2022.pdf

[32] SRC (2021) Decadal Plan for Semiconductors. Retrieved from https://www.src.org/about/decadal-plan/decadal-plan-full-report.pdf

[33] NIST (08/03/2022) NextG Wireless R&D Gap Analysis Workshop, Data Availability, Use, and Privacy (U.S. Department of Commerce, Washington, D.C.)

instructing networks and devices with diverse information. This may include a new data plane with enhanced infrastructure for physical and virtual resources for a new heterogeneous structure.

### Data Availability and Use

50. **Need to develop new protocols and technologies to collect, standardize, and store structured, unstructured, and semi-structured data:** Data for wireless communications comes in three forms: 1) structured which is clearly defined and easy for searches; 2) unstructured which is not stored in a database format; and 3) semi-structured which have structured properties but the majority of its content is unrelatable. Due to the massive amount of new data a NextG architecture would generate through various devices, there needs to be a standardized method for data collection and standardization. This would allow different layers of the network stack to work concurrently and for operators to have better visibility in network operations. Processing data at the edge will be helped by core data centers with access to application data through the radio environment.

51. **Need to improve network resiliency by guaranteeing the availability of data supporting NextG network operations and analytical functions:** From a NextG perspective, data centers can no longer be at the center of the network, as processing will move to the edge for faster speeds. This will require a distributed cloud infrastructure with smaller data centers communicating with the core network and large data centers.

52. **Need to develop secure, private local data computing processes:** 5G standardization represented a technology effort to increase bandwidth, decrease latency, and optimize other network performance advancements that resulted in excess capacity. Working Group participants expect more devices and data-intensive applications to make use of this excess capacity as the industry transitions to NextG. Therefore researchers need to create sustainable power consumption of networks, economies, and privacy for personal data. The amount of data from sensors will grow exponentially with the proliferation of intelligent surfaces, small cell networks, and personal devices. Much of this data will be personally identifiable and therefore requires secure local computation and backhaul to the cloud. Participants noted that where and how NextG data is computed matters.

53. **Need to enhance data availability through replication for machine learning failures:** Previously proposed replication schemes cannot effectively handle both correlated and uncorrelated machine failures, especially while increasing the data availability with limited resources. The schemes for correlated machine failures must create a constant number of replicas for each data object, which often neglects diverse data popularities and does not utilize the resource to maximize the expected data availability. Also, the previous schemes neglect the consistency maintenance cost and the storage cost caused by replication.

### Privacy and Security Enhancing Technologies

54. **Need to increase trust and confidence in data:** Working Group participants discussed a variety of NextG data privacy applications and enabling technologies that would increase user trust and confidence in emerging applications that leverage sensitive data. These technologies enhance personal and organizational privacy for NextG computing tasks such as dissemination of data, XR, biometric identification, and IoT device coordination.

55. **Need to develop privacy-enhancing technologies that enable individual authentication and identification, and new data-driven networks and applications:** NextG applications require improved analytic, identity management, and encryption technologies to more effectively protect user privacy while maintaining access to location-based, proprietary, or otherwise sensitive data sources expected to support advanced communications use cases. Working Group participants noted that existing encryption and privacy-enhancing technologies do not fully address the demand for expanded or shared access to potentially sensitive datasets, nor fully protect user privacy. Thus, more research is required to develop new technologies, standards, and protocols to manage access to data relevant to NextG use cases while protecting user privacy and empowering users to make informed, intentional data sharing decisions.

56. **Need to develop frameworks for encrypting data during analytical processing:** Current data encryption models protect data in motion and at rest but not during use. DARPA's Data Protection in Virtual Environments (DPRIVE) program seeks to achieve Fully Homomorphic Encryption (FHE) which encrypts data during the processing cycle. The current problem with FHE is the large computational time for processing data and catching up with unencrypted processing. DPRIVE plans to build a specific hardware accelerator for this problem and achieve within 10x of unencrypted processing time. Participants noted that additional research is required to determine how to make encrypted data processing algorithms more computationally efficient.

57. **Need to develop more energy-efficient computing hardware to securely process data on local devices:** Even with specialized accelerators for secure computing, complexity/energy consumption remains a problem. The sorting of data and operations can help security where only a subset of computing happens on secure hardware.

58. **Need to create communications data security standards that align with future generation network specifications:** Ongoing research in the context of the DARPA program DPRIVE on the use of FHE has tackled the development of novel hardware to enable data and privacy protection. However, there is a need for policies on issues like key management, side-channel attacks, and leakage of information. In order to make it effective for all users, FHE technology needs to align with 3rd Generation Partnership Project (3GPP) standards.

59. **Need to develop a joint communications and computing system architecture that emphasizes network security and data privacy:** Working Group participants noted that 5G standards do not define a common architecture for integrating secure communications and computing capabilities. Therefore moving forward, communications systems may need to be more closely integrated with computing processes so that self-privacy preserving techniques for applications could be run within a generally available communications/computational network.

60. **Need to develop new privacy metrics for secure, integrated joint communications and sensing networks:** Researchers need to develop new privacy metrics that are both intuitive and may be implemented across communications, radar, and joint sensing networks. New empirical privacy quantification metrics are also needed that can allow for quick evaluation of privacy leakage and protection of proposed approaches. Wireless signals are susceptible to adversarial attacks. As mission-critical NextG systems are designed, researchers need to integrate solutions and privacy monitoring approaches to ensure reliable, secure communications.

# NIST Data Privacy Framework

The NIST Data Privacy Framework[34] was developed to assess individual privacy risk factors and implement unique tools for mitigation. It defines privacy risk assessment through a logic model and is built on the objectives of predictability, manageability, and dissociability. NIST developed this model to help individuals track and keep autonomy over personal data, which Working Group participants view as critical to the long-term viability of data-intensive NextG applications. NIST detailed several privacy engineering objectives for stakeholder feedback that include:

- **Predictability:** Enabling reliable assumptions by individuals, owners, and operators about data and their processing by a system, product, or service. This allows each organization to effectively tailor privacy controls.
- **Manageability:** Providing the capability for granular administration of data, including alteration, deletion, and selective disclosure. These objectives provide metrics for privacy controls.
- **Dissociability:** Enabling the processing of data or events without association to individuals or devices beyond the operational requirements of the system. This allows for organizations to process data without individual association.

NIST also described several concepts that R&D organizations should consider as they begin integrating data privacy frameworks with their NextG communications products and services. Key data privacy concepts reviewed by the working Group include:

- **The Core:** Provides an increasingly granular set of activities and outcomes that enable organization dialogue about managing privacy risk.
- **Profiles:** Defines a selection of specific functions, categories, and subcategories from the core that the organization has prioritized to help it manage privacy risk.
- **Implementation Tiers:** Helps an organization communicate whether it has sufficient resources in place to manage privacy risk and achieve its target profile.
- Stakeholders reviewed NIST's Privacy Risk Assessment Methodology to follow a consistent logic model illustrated in Figure 2. R&D organizations can use this assessment workflow to identify organizational data privacy risks inherent in NextG systems under development and implement governance or technology controls to maintain privacy while user data is stored, in transit, or viewed by NextG applications.

[34] NIST (2022). NIST Data Privacy Framework. (U.S. Department of Commerce, Washington, D.C.), Available at: https://www.nist.gov/privacy-framework

# NIST Data Privacy Framework

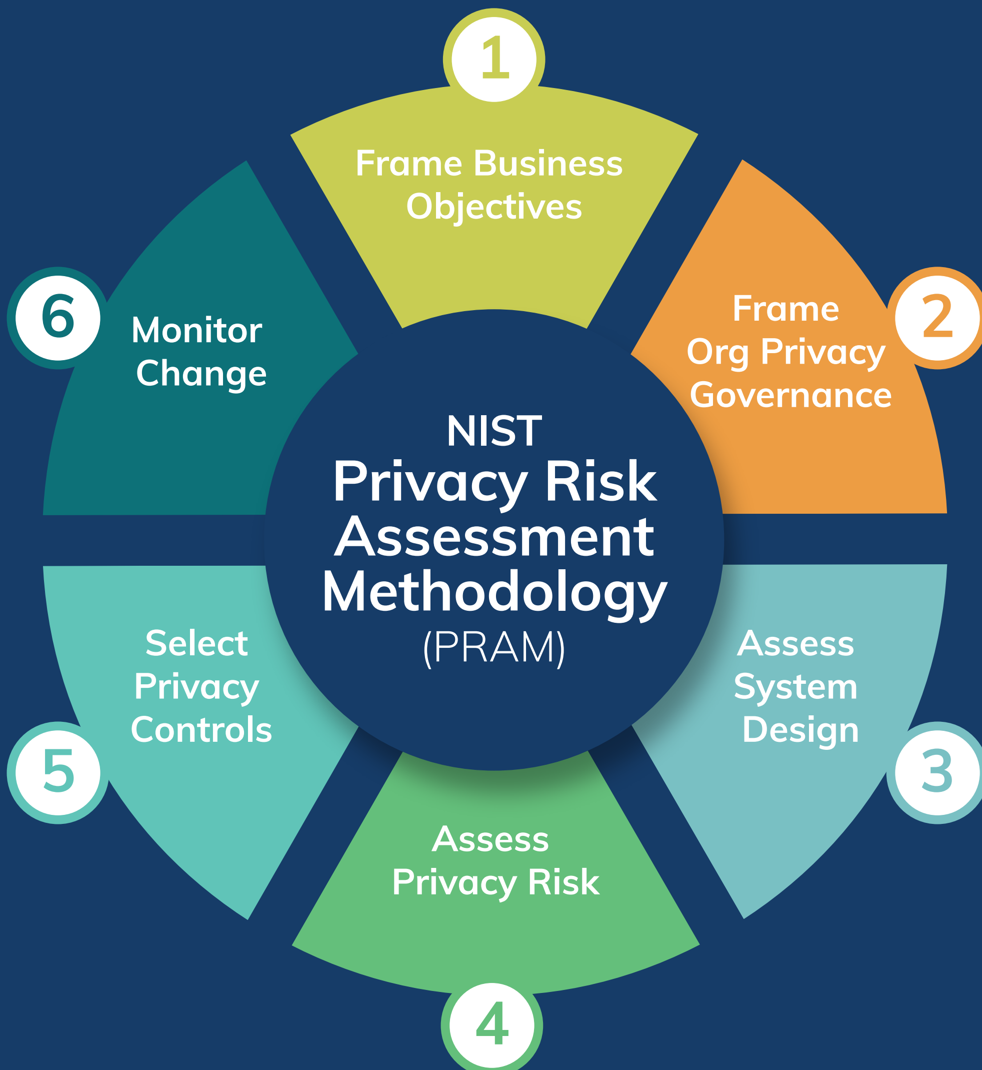



*Figure 2:*
*The NIST Privacy Risk Assessment Methodology*[35]

[35] NIST (08/03/2022) NextG Wireless R&D Gap Analysis Workshop, Data Availability, Use, and Privacy (U.S. Department of Commerce, Washington, D.C.)

### Data Privacy Technologies and Governance

Working Group participants identified several technology and data governance challenges that represent important gaps to address before the widespread adoption of NextG capabilities. These gaps include:

61. **Need to define privacy and risk management tools for NextG systems:** Tools and guidance documents like NIST's Privacy Risk Assessment Framework are quite new, and the communications R&D community lacks a vocabulary to correctly frame data privacy problems and corresponding technical solutions. Organizations are using personal data to achieve a mission with unintended consequences that can have a direct impact on individuals. Since privacy risks are events that arise from data processing, the privacy risk assessment finds vulnerabilities from data collection through disposal.

62. **Need to define data vulnerabilities, privacy risks, and mitigation strategies across all levels of NextG system components before implementing technologies to safeguard data:** Privacy risks that arise during data processing may cause affected individuals to experience direct impact including embarrassment, discrimination, or economic loss. Affected organizations may experience customer abandonment, noncompliance costs, and harm to reputation or internal culture.

63. **Need to implement dissociability technologies that support defined organizational data privacy objectives:** Working Group participants discussed a variety of technical concepts that NextG R&D organizations could explore to limit privacy risk in their products and services. Technologies in need of further research include dissociation processing solutions that process user data, while protecting individuals' privacy and enabling the implementation of privacy principles (e.g., data minimization). R&D organizations should also consider data processing techniques that limit, the observability and linkability of user data; the identification of individuals; and the formulation of inferences about individuals' behavior or activities.

64. **Need to increase the security of distributed computing across wireless networks:** Working Group participants noted that security issues affecting wireless networks represent a distributed computing challenge. NextG data privacy is not only concerned with securing data while in transit but while computational devices process and store communications data. Communications and computing researchers both need to worry about integrating "security management" into all aspects of system architecture such as key distribution and the assessment of trust in different network nodes,in different countries, or with simple devices attached to the network. Researchers should consider how much security management techniques are built into 3GPP-type standards, and the degree to which they are integrated into internet-type standards.

    - In terms of privacy, stakeholders recommended that standard bodies for Wi-Fi and 3GPP should work together to create aligned objectives.

    - Security and privacy depend on the situational adversaries. Security goals can be defined from the angle of how to protect a computer system (such as cloud servers) against outsider attackers while defining privacy goals as how to protect individual users' rights against powerful computer servers (such as cloud servers).

- Security management needs new metrics to measure the robustness and security of solutions. Such solutions are needed to drive optimal strategies that are currently lacking.

65. **Need to consider existing cryptography algorithms for enhanced security:** Cryptology algorithms can almost guarantee the safe transfer of data between two parties. NIST and other R&D organizations have invested significant resources to prepare for quantum communications through cryptographic standards initiatives and calls for post-quantum cryptography. These standards are able to provide quantum-safe alternatives to current public key cryptography standards. There is limited availability of public research designs for ensuring security against quantum computers. One example is a system that increases the size of digital keys so that the number of permutations from an attack uses immense computer power. This defense puts the barrier for entry of an attacker too high for enterprise-wide attacks. Working Group participants emphasized the need for expanded research into network security protocols designed to limit vulnerabilities exploitable by quantum computers.

### Confidential Computing and Privacy Engineering

Working Group participants discussed the long-term vision for confidential computing capabilities supporting increased data privacy expected for NextG systems. Confidential computing technologies preserve personal information by giving the user choice at the point of data availability and sharing. Integrating privacy engineering capabilities into NextG systems may enable individual user-driven choices about data sharing and availability, rather than assigning enterprise- or application-wide privacy controls to communications and computing service providers that leverage user data during operations.

66. **Need to define user and service provider requirements for a "trustworthy Data Economy:** There is a need to create a trustworthy NextG Data Economy driven by producer control of user data and multi-cloud infrastructure. Confidential computing capabilities present the opportunity to maintain privacy-preserving data infrastructure while meeting NextG network, device, and application performance expectations. Working Group participants also recommended the R&D community develop or certify trustworthy data markets in which users can monetize a portion of their personal data while protecting other data attributes through privacy guarantees.

67. **Need to develop a distributed confidential computing architecture:** Confidential computing is a principled, verifiable security mechanism for distributed computing. It is more effective than enterprise security engineering management, because it empowers data owners to control who sees and how they see the data. It protects the integrity and confidentiality of processing wherever programs run and protects data from malicious programs or careless insiders. This capability also has the possibility of removing the infrastructure provider, such as network operators, from the chain of trust. It is built upon four capabilities:

    - Isolation: Program addresses space and computation.
    - Measurement: Use of cryptographic hash to create an unforgeable program identity.
    - Secrets: Isolated storage and exclusive program access.
    - Attestation: Enable remote verification of program integrity and secure communications with other such programs.

68. **Need to identify cross-sector applications for privacy engineering technologies:** Confidential computing should be researched in the cloud, networking, and telecommunications sectors for better understanding and application. Because NextG applications require low-latency network data processing, it will be important to move computing closer to the edge. The ideal scenario removes the cloud provider from confidential computing processes and therefore exposes the organization to potentially fewer security vulnerabilities.

69. **Need to more clearly define the business case for enhanced confidential computing security:** Increased computing cost may limit broad confidential computing applications. In order to overcome the cost penalty, there is a possibility to introduce a subset of highly secure services with full confidential computing security management. There can certainly be selective use of confidential computing for security gains, such as the network infrastructure. Working Group participants noted that introducing confidential computing capabilities to specific components of the network would not significantly increase the power consumption and associated energy cost increases required for network operations.

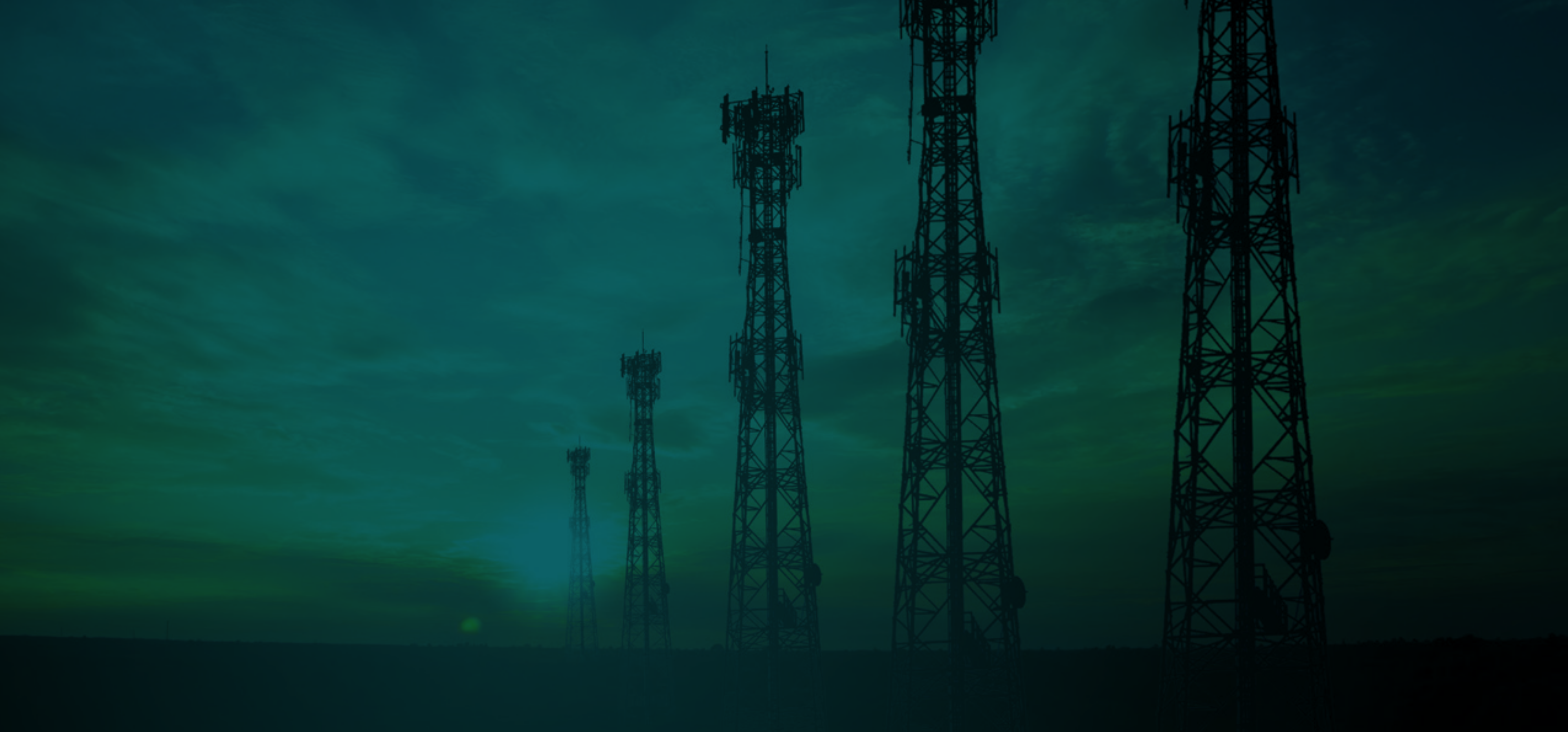
### Post-Quantum Cryptography and Quantum Key Distribution

In the age of Quantum Computing (QC), the definition of a quantum-resistant security framework becomes a top priority for NextG. This strategy relies on the use of Post-Quantum Cryptography (PQC), through unbreakable cryptosystems, as well as on the exploitation of Quantum Key Distribution (QKD), which is based on the laws of physics to achieve secure transmission. NIST is leading a program [36] to evaluate a range of PQC algorithms towards the development of standards.

70. **Need to consider QKD for enhanced security:** QKD can almost guarantee the safe transfer of data from two parties. QKD can greatly increase the security of data by utilizing QC and wireless and/or fiber optic cable.

71. **Need to study the integration of QKD into the NextG infrastructure:** As quantum resources are integrated into NextG infrastructure for securely distributing keys to NextG terminal nodes, there is a need to explore the co-design and synergy between applications. This need for exploration is based on photonic quantum bit (qubits) propagation over the deployed fiber infrastructure. In addition, one of the main unsolved problems of qubits is the fragile state they maintain during transmission. The temperature of the electrons and photons utilized for qubits must be maintained in a deep freeze close to the temperature of deep space. This presents a challenge as a fluctuation in temperature can cause qubits to collapse and lose their superposition properties.

[36] NIST (2022) Post Quantum Cryptography Workshop (U.S. Department of Commerce, Washington, D.C.), Available at: https://csrc.nist.gov/Projects/post-quantum-cryptography/workshops-and-timeline



# NextG Network Architectures

As more devices are connected, different Wi-Fi, cellular, and satellite networks need to seamlessly interoperate to enable end-to-end services that leverage shared hardware, software, and data storage resources. This convergence will reduce cost and improve the quality of the types of services users will need to buy in the future. This advancement helps both operators and users alike but comes with technical and policy challenges. While the network architectures of the last half century have revolved around users and their applications (voice, video, messages, etc), the increased dominance of sensors and machine-to-machine type communications in NextG systems to be developed constitutes a significant paradigm shift. And while prior network generations have emphasized faster speeds, lower latency, and greater reliability, NextG systems will advance complementary aims of truly global coverage, sustainability, and security.

Future generation network architectures will need to feature more flexible access technologies that can accommodate more devices and sensors with disparate operating systems. Network design, architecture, policies, protocols, and antennas will need to become increasingly dynamic, rather than static, in order to manage resources efficiently in this new system. Extending current architecture models – those that rely on cell towers, fixed dishes, and macrocell nodes – will not be enough to accommodate the exponential increase in connected applications, data flows, and devices. Augmenting the cell tower or fixed dish model with expanded use of technologies, such as deployable networks, mobile hotspots, and Massive MIMO antenna arrays, will lead to increased network capacity and coverage. However, these supporting technologies need to be designed with respect to cost, scalability, spectrum, and form-factor requirements that are still being defined.

### Convergence and Heterogeneity

72. **Need to study computing and telecommunications convergence:** The convergence between fixed, mobile, nomadic, and satellite communications and cloud computing under a single framework will enable seamless information flows across multiple devices, infrastructures, and assets. New architectures may be adapted/optimized for semantic or task-oriented

communicationsNextG network infrastructure should be ubiquitous and not limited by the coverage of radio communication networks. Data traffic should use all access technologies available according to their strengths, whether that be fixed networks, cellular networks, or satellite networks. This will ensure cost-effective, agile, robust, resilient, and adaptable delivery of communications and computing services that align with end-user demand at any location and at any time.

73. **Need to support Machine-to-Machine (M2M) Communications:** Working Group participants envisioned that M2M network architectures will become more wireless, scalable, and ubiquitous in NextG systems. Through enhanced analytics, M2M systems will learn to automatically buffer incoming or outgoing data transmissions when systems exceed processing capabilities, due to the volume of data exceeding network capacity. The Working Group highlighted several challenges that the R&D community needs to address before realizing these capabilities. Identified challenges include the ability to prioritize M2M network traffic and data quality during peak times, the lack of standards to guide the collection and transmission of data sourced and processed by different devices, and the deployment of M2M network endpoints at the edge that can operate without centralized data processing centers. M2M also faces severe challenges from data loss on industrial IoT devices, but that improved M2M data storage capacity at the edge of the network would enable connected devices to more effectively complement one another based on system activity.

74. **Need to fundamentally redesign the architecture of the network to bring computing and communications resources together without end-to-end latency:** Edge computing and AI should be treated as native components of NextG communications networks and applications. Local, interoperable analytic functions at all levels of the network will be essential for moving intelligence from the central cloud to the edge of the network and ensuring end-to-end orchestration of workloads across both the communications and computing domains. To realize this vision,the communications standards development community responsible for defining NextG system specifications should consider requiring the native implementation of computing and AI functions

75. **Need to enable user equipment to communicate directly in short range, using device-to-device (D2D) communications protocols:** With its intelligent mobility management technology, NextG should enable data traffic to be offloaded to the best access technology. For instance, traffic could be carried over D2D or Wi-Fi in the case of short-range use cases when convenient; over satellite communications in the case of airspace, sea, and lands not covered by terrestrial communications; or the traditional terrestrial communications in the case of wide area networks coverage.

76. **Need to study mobility management of network architecture:** The alignment of beams has implications for design control, such as user tracking, handover, and radio link failure recovery. In this architecture, there must be a calculation between the end user and satellite depending on velocity for Doppler frequency shift. The high velocity of non-terrestrial satellites is the main concern as alignment becomes increasingly important.

### Rethinking Communications Network Layers

77. **Needs for new Medium Access Control (MAC) and Physical (PHY) layers:** Working Group participants identified opportunities to improve the capacity, flexibility, and performance of the PHY, MAC, and Data Link Control (DLC) network layers. The growth in the heterogeneity of technologies supporting NextG use cases requires more precise, scaled orchestration of activities across these network components. To provide sufficient network agility required for NextG use cases and reduce barriers for introducing new technologies, the R&D community needs to develop new PHY and MAC techniques that can more effectively be integrated into post-5G standards.

78. **Need to explore how application programming interfaces (APIs) can improve the flexibility and interoperability of network layers:** API-centric approaches may allow compatibility and system integrity while allowing innovation and customizability. Working Group participants shared that the current approach for coordinating the operation of different network layers is highly prescriptive of all aspects of a system and can in many cases freeze out innovation and create friction and inefficiencies in standards. Currently, in 5G, there is an overlay of many quasi-sedimentary layers of successive legacies, from conventional suboptimal modulations to interleaving over channels, to being limited to a small number of long and low-rate physical layer codes, such as low-density parity-check code, to hybrid automatic repeat request (ARQ) and ARQ repetition at the MAC and transport layers. 5G has often resorted to increasing bandwidth to mask the inefficiencies of these legacy issues by running systems faster. Higher bandwidths are onerous, from the monetary cost of the leasing spectrum to the attendant energy overhead of processing. At the PHY layer, one can consider the example of PHY Forward Error Correction and Modulation. Similarly, replacing current modulations with optimized ones can provide large gains in performance. This replacement should be allowable as long as modulations do not interfere with other signals. At the MAC level, replacing traditional hybrid ARQ and non-traditional ARQ with flexible approaches, particularly network-coded versions, will provide considerable increases in rate, reductions in latency, and the sort of reliability that can truly instantiate ultra-reliable low-latency communications.

79. **Needs for a new Data Link Control (DLC) layer:** The integration of new frequency bands into NextG systems enables a variety of new wireless applications. However, the proliferation of different frequencies without an effective, standardized means of integration is highly suboptimal for network stacking. Blending is limited or absent in 5G, but it will be critical in NextG if the multiplicity of types of channels (e.g., different frequencies with significantly different channel properties, satellite, Wi-Fi) need to be used efficiently. Researchers have found emerging multipath systems, aided by network coding to avoid the difficulties of scheduling, as promising ways to integrate the use of different PHY technology. Again, the use of APIs, in a manner akin to sockets, may permit incorporation without the need for prescriptive standardization.

80. **Need to research new Transmission Control Protocol (TCP) algorithms for optimal higher bandwidth use:** The current transport protocol congestion control schemes do not perform well with higher bandwidth (mmWaves and THz) for end-to-end performance. The inefficient interplay between contention-based access controls and transport control protocol timers triggers timeouts and congestion recovery. There is a need for new protocols that can

combine the physical and virtual layers of the network for end users with different bandwidth requirements. Also, if the latency is expected to remain, applications of communications links must take this into account for vital communications supporting smart utility grids or other IoT functions. Currently, the end device or demand-side management of bandwidth studies is assuming perfect telecommunications conditions.

### Openness and Virtualization

81. **Need to integrate and accelerate the development of Open Radio Access Networks (OpenRAN):** Building virtualized Radio Access Networks (RAN) on open-source hardware or cloud hosting platforms may provide greater agility for current and future communications networks. Managing OpenRAN operations through AI-driven radio controls has potential to increase the ability to unify disparate software applications supporting a network; deployment flexibility; and real-time responsiveness for low-latency activities. Working Group participants also noted that OpenRAN technology may reduce communications system operating costs by unifying the connectivity gains of all generations (1G through 5G) into a single, fully-interoperable mobile network.

82. **Need to lower the barrier for network entry through open-source software:** Most base stations are not common or open-source software and therefore it is hard to configure a new network through joint programming of the packet core and RAN. NextG networks must decentralize network capacity to a distributed set of wireless nodes that will enable faster and more scalable communications by regionalizing, or layering, components of the core network to reduce backhaul requirements.

83. **Need to transition from fixed tower architectures to a number of deployments through edge computing and local processing:** The demand for increased bandwidth and reduced latency puts pressure on cloud-based networks to push computing capabilities closer to the user. The need for edge computing and local processing will necessitate researchers to overcome a cognitive barrier to shift from traditional fixed tower architectures (one-to-one) to architectures with a greater number of deployable components (one-to-many).

84. **Need to decrease intercloud and link queuing delays for end-to-end connectivity:** As the number of requests for transmissions increases, the links between networks need virtual network functions to be placed strategically for lower latency. Network functions virtualization (NFV) replaces network appliance hardware with virtual machines. NFV uses virtualization technology to run network functions on software that can be moved through different network locations. This will help address the problem of allocating resources at the edge of the cloud. This will require batch-based network service chaining, routing, and placement.

85. **Need to study device-device and device-network computing scaling for wide-area cloud:** Cloud infrastructure currently relies on client-server applications, instead of distributed computing, for dynamic scaling. Distributed computing can allow the server-side workload to run on high-end mobile devices or network nodes. This model complements edge computing and requires a robust cloud infrastructure for implementation. The scalability of this model requires better power consumption,energy conservation, latency, and network condition.

# Non-Terrestrial Networks

Non-terrestrial networks (NTN) are a key component to NextG wireless systems, providing ubiquitous, cost-effective and high-capacity connectivity to both fixed and mobile user devices across the globe.[37] Notably, while previous wireless generations have been traditionally designed to provide connectivity for an essentially two-dimensional space, NextG envisions a three-dimensional heterogeneous architecture in which terrestrial infrastructures and non-terrestrial stations -including satellites, UAVs, and HAPS– form part of a single integrated mobile service. Not only can these non-terrestrial elements extend mobile service to provide ubiquitous mobile coverage and on-demand, cost-effective coverage in crowded and unserved areas or during public emergencies, but they can support a range of applications, including IoT services, trunking, backhauling, support for high-speed mobility, and high-throughput hybrid multiplay services.

Nevertheless, there are still several questions to be answered for proper network design, in particular those related to spectrum usage, medium access and higher layers, coverage, and mobility management constraints, as detailed below.

86. **Needs for non-terrestrial channel models:** Even though the 3GPP has specified how to characterize high-frequency propagation (e.g., in the Ka-bands) for the satellite channel, 3GPP is currently not investigating second-order statistics related to space and time correlation, nor the impact of Doppler, fading, and multipath components, which are critical at high frequencies. Moreover, a general and accurate model of a fully-layered space-air-ground channel, especially channel models for low- and high-altitude platforms like drones and aerostatic balloons, respectively, is still lacking.

87. **Need for high-capacity communication:** NTNs operate across a wide range of frequencies, including, in the legacy frequency bands below 6 GHz (S-bands) and higher frequencies, such as

[37] Marco Giordani, and Michele Zorzi, (2021) Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities IEEE Network, vol. 35, no. 2, pp. 244– 251. https://ieeexplore.ieee.org/document/9275613

the Ku-, Ka, Q/V, E-band and other mmWave frequency bands. These higher-frequency bands offer significant and critical bandwidth to support ultra-fast backhaul and end-user connections. Lower frequencies have been used in the 5G market for both cellular and vehicular networks, although deployment of mmWave frequencies for cellular networks remains relatively limited to use cases such as satellites offering weather forecasting services. Challenges affecting the use of mmWave frequencies for NTN use cases compared to terrestrial broadband communications include severe path loss experienced at high frequencies, longer propagation delay, and environmental attenuation including more severe atmospheric disturbances.

88. **Needs to achieve spectrum co-existence:** As NTNs increasingly depend on mmWave bands to serve a growing number of consumers and use cases, consideration needs to be given to the coexistence among different networks. The main challenge with spectrum coexistence is the development of flexible spectrum sharing and interference management techniques that maintain adequate isolation among different communications, while ensuring reasonable licensing costs. Many organizations, including satellite and HAPS operators, have proposed flexible, static sharing regimes in mmWave bands, particularly extending database-assisted light-licensing frameworks to enable self-coordinated sharing between terrestrial and satellite services.

89. **Needs to develop the uplink:** In the downlink, non-terrestrial nodes (especially satellites) can mount massive circular aperture antennas offering sufficient gain to compensate for the very long transmission links and low antenna gain on the receiver. In the uplink however,limited antenna gain due to small handset antennas may prevent high-capacity direct handset-to-satellite communication. Additionally, the time introduced by RAN operations, from routing and scheduling to resource allocation and modulation, can affect latency in the uplink.

90. **Need to decrease Round Trip Time (RTT) in non-terrestrial networks:** There are a few different NTN architectures that will experience different RTT between ground devices and the satellite, including Low Earth Orbit (LEO) with satellites between 500 to 2,000 kilometers (km), Medium Earth Orbit (MEO) of 10,000 to 20,000 km, Geostationary Earth Orbit (GEO) with an altitude of 35,000 km above the equator, and High Altitude Platform Systems (HAPS) that are airborne objects ranging from 15-400 km. Each architecture presents differing coverage, latency, and throughout characteristics, while also experiencing different operational factors, such as satellite co-existence, differing beam footprints, and geo-location. The use of these satellites and transmitters will have to be configured and changed for individual devices by the least RTT which will require a configuration of OpenRAN. The non-terrestrial network will need flexible spectrum-sharing techniques for the co-existence of the spectrum on different networks. As more satellites are incorporated into the network, coordination between non-terrestrial and terrestrial networks is needed, as they will run on similar bands. In mmWave bands, this coordination can be facilitated through database-assisted light-licensing, which generally can be managed on a self-coordinated basis.

91. **Needs to develop PHY-layer procedures:** In NTNs, even the highest available subcarrier spacing in the frame structure may not be enough to compensate for the large Doppler experience considering the high speed of aerial/space stations. Moreover, the large propagation delays in NTNs may create a larger response time for the adaptive modulation and coding scheme loop and require a margin to compensate for the possible outdated control signals exchanged during channel estimation. Notably, in an integrated terrestrial/non-terrestrial framework, different network elements on the end-to-end communication path may process the information at

different rates, thus contributing to the overall communication delay. Additionally, TDD, which is frequently considered in terrestrial networks, may be infeasible in NTNs, since guard times must be proportional to the propagation delay.

92. **Needs for synchronization:** NTNs are fast-moving, and typically feature larger cells compared to terrestrial networks. At low elevation angles, this may create a very large differential propagation delay between users at the cell edge and those at the center (up to 10 ms for GEO satellites), thereby raising synchronization issues.

93. **Needs to explore resource saturation in high-density scenarios:** A non-terrestrial station has a much larger footprint than a terrestrial cell, and is required to serve a larger number of on-the-ground terminals. This may result in saturation of the available bandwidth, with strong implications for latency and throughput performance. In this case, orchestration with terrestrial infrastructures becomes important.

94. **Need to develop initial/random access and channel estimation:** Initial access makes terrestrial terminals establish a physical connection with a non-terrestrial station by detecting synchronization signals. This is particularly challenging in NTN applications, where the channel may vary quickly over time, as the initial estimate may rapidly become obsolete.

95. **Needs for mobility/constellation management:** Satellites may operate through high-spot directional beams to achieve a sufficient link budget, especially when operating in the Ka-bands to maintain high-capacity connections. In this case, fine alignment of the beams has severe implications for the design of control operations, (e.g., user tracking, handover, and radio link failure recovery). These challenges are particularly critical for NTNs, where the very high speed of aerial/space platforms could result in loss of beam alignment before a data exchange is completed. The increased Doppler encountered at high speed could also make the channel nonreciprocal, thus impairing the feedback over a broadcast channel.

    Additionally, air/space-borne vehicles move rapidly relative to the Earth's surface. For example the orbital velocity of a LEO satellite is around 7.8 km/s, and the visibility period of the satellite is a few minutes.The vehicle's rapid movement relevant to the Earth's surface may create regions where coverage is not continuously provided. A constellation is thus necessary to maintain ubiquitous service continuity. When configuring multiple satellites, that move in different orbits, to operate in an integrated framework, the constellation management is hindered by handovers and load balancing among the different layers.

    Moreover, considering the large cell size of NTNs, many devices may be served within a single cell. Depending on constellation assumptions (e.g., propagation delay or satellite altitude and speed) and the density of terrestrial devices, a potentially very large number of devices may need to perform a handover at a given time, leading to possibly large signaling overhead and service continuity challenges. For example, the 3GPP estimates that, for a cell diameter of 1,000 km and assuming around 65,000 connected devices (i.e., the average device density is 0.08 devices/km2), the average time required for handover may be as large as 132 seconds. [38]

    The R&D community may investigate how fiber connections could coordinate between terrestrial

[38] John Meredith, Joern Krause, Patrick Merias (2019) Study on New Radio (NR) to support non-terrestrial networks. (3GPP) (Release 15), TR 38.811. https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3747

base stations and the backhaul; and how advanced wireless technologies could coordinate non-terrestrial air/space-borne stations to build an NTN system that overcomes the complexities associated with constellation management.

96. **Needs for the higher-layer protocol (re)design:** Current network/transport protocols may show poor performance when NTNs are involved. First, topology information may quickly become obsolete (especially considering unpredictable mobility, e.g., for UAV swarms) and must constantly be refreshed, thus increasing the communications overhead. Second, a large RTT results in a longer duration of the slow start phase of TCP, during which the sender may take inordinately long before operating at full bandwidth. Third, sudden drops in the link quality, which may be common in NTNs, make the sender reduce its transmission rate, thus leading to a drastic decrease in resource utilization. Finally, when a multi-layered integrated network is considered, different network devices may support different (and sometimes conflicting) communications protocols, thus complicating network management.

97. **Needs for multi-layered integration:** Standalone NTNs (especially considering satellites) introduce new challenges for the whole protocol stack, including those associated with latency and coverage constraints. On the other hand, the availability of multi-layered hierarchical networks, where intermediate aerial/space platforms act as a relay of an upstream device, can provide superior coverage and resilience performance compared to standalone systems. In this context, there are still various questions to be answered for proper network design. Working Group participants particularly focused on the outstanding question of which degree of integration results in better spatiotemporal coverage.

98. **Needs for energy efficiency:** Due to the large distances involved in the NTN scenario, and the resulting severe path loss experienced, the uplink transmit power is typically set as close as possible to the saturation point. This could reduce the duration of batteries, which is particularly critical in scenarios where terrestrial sensors are used to support IoT applications. Additionally, UAVs incur high propulsion energy consumption to maintain and support their movement, thereby posing severe power management constraints. Finally, while HAPS and satellites implement solar charging technology to provide long life and stable wireless connectivity, it is still unclear whether solar panels can produce or harvest enough power to support communications, caching, and computation activities.

99. **Needs to address space debris:** The LEO environment is becoming congested with space debris because of the increasing frequency of object launches. Notably, when an LEO satellite reaches the end of its life, it will be deorbited into the Earth's atmosphere to burn up, which may take months to complete. During this process, the satellite acts as space debris, which increases the congestion level and risk of collision. Collisions can further produce additional space debris, creating a domino effect known as Kessler syndrome. To date, the Orbital Debris Program of NASA has tracked over 25,000 objects larger than 10 centimeters in the LEO environment. At speeds up to 17,500 miles per hour, such objects are fast enough to damage a satellite or a spacecraft. The research community should develop new solutions to track and predict the presence of debris and implement automatic maneuvering algorithms for spacecraft to react accordingly.

100. **Needs for air/space-borne architectural technologies for computation:** NTNs differ from typical terrestrial cellular networks in terms of architecture, deployment scenarios, as well as coverage and latency constraints. Potential impacts on the standard 5G NR specifications due

to NTNs could be minimized through suitable mapping options of the NR-RAN architecture onto the NTN-RAN architecture. Besides providing connectivity, NTNs can also host edge servers for processing, caching, and/or storing data, e.g., for power-constrained devices with limited computational capability. However, while air/space-borne platforms have less computational/energy constraints than terrestrial devices, the operational characteristics of those networks may jeopardize data offloading, thereby making the design of these systems non-trivial. At the same time, it is still unclear where to distribute computing planes, based for example on Software Defined Networking (SDN), for proper service delivery; the choice depends on different factors, like the available processing capabilities or the achievable transmission rate.

101. **Needs for security and privacy:** The R&D community designing an integrated space-air-ground architecture should envision the existence of a trusted central authority making secure network topology and communication decisions to prevent malicious nodes from being selected as a gateway.

102. **Needs for the design of smart sensors for positioning and monitoring:** The physical proximity between the aerial/space nodes (especially UAVs, HAPS, and LEO satellites) and potential targets on the ground improves optical sensors resolution. Improved optical sensor resolution may offer the same sensing efficiency with lighter payloads and smaller size, or incorporating more capable platforms at the same cost. Potential beneficiaries of this condition are applications to support autonomous driving and/or positioning.

103. **Needs to reconcile mismatches between 3GPP and International Telecommunications Union (ITU) parameters and existing deployments:** The LEO environment includes both nano/picosatellites—which incorporate simple electronic devices to reduce component and launch costs, and are constrained by limited power and antenna gains—, as well as more advanced satellites designed to provide broadband and direct-to-handset capabilities. Mobile operators and NTNs have also entered into partnerships that enable mobile operators to extend their existing spectrum holdings through space-based connectivity. The 3GPP and ITU have released a set of specifications for the antenna/channel/deployment models of LEO constellations,34 which depend on the operational frequency, satellite altitude, and other configurations. Hardware and spectrum constraints based on the 3GPP/ITU models can potentially make LEO communication (or relaying) difficult and restrict beneficial innovation. Further work should be done to make sure that 3GPP/ITU specifications and mobile allocations are flexible enough to accommodate current industry trends and partnerships integrating space-based NTNs.

# Sustainable and Energy-Efficient Networks

Communications systems consume energy through a variety of technologies supporting end-user devices, RAN, and computing functions in the cloud, data center, or network edge. NextG systems need to leverage streamlined computing processes, more power-efficient radio transmission, and user devices. This will help rethink network architecture to meet expectations related to the sustainability and energy efficiency of future systems. The increased diversity of available devices presents unique power management and sustainability challenges related to network energy analysis, spectral vs. energy efficiency, and base station power.

104. **Need to develop energy consumption models and metrics for NextG systems:** Network simulation models focused on energy consumption need to incorporate spectral efficiency, low power operating modes, improved Massive MIMO deployment, and energy harvesting. More granular energy consumption metrics will help the R&D community better understand system performance tradeoffs and optimize energy efficiency between networks and utility providers. System-level KPIs for NextG energy usage are needed to justify the return on investment for small cell deployments and equipping sensor endpoints with passive power operational modes. Establishing a new set of NextG energy consumption metrics will also increase the feasibility of setting realistic utility incentive programs and payback period analysis to incentivize NextG deployments. A wider variety of network and computing operators will require standardized payback algorithms that acknowledge dependencies between financial viability, network performance, and hardware reliability across diverse operating environments to support NextG use cases. Developing reliable models to test and validate network energy models represents a complex, emergent gap. The communications R&D community needs to establish a basic framework and develop validated energy cost of ownership and energy savings models for NextG systems.

105. **Need to ensure power efficiency gains associated with small cell deployments offset base station energy usage:** Researchers should advance the control and automated coordination of small cells and cell-free architectures to ensure they consume less power than what is saved across the overall network. As devices move further away from the power source, it will require more energy. The small cells must be deployed precisely where they are needed (e.g., traffic hotspots, city centers) to ensure the small cell's marginal energy consumption increase is offset by the subsequent reduction in energy consumption from the macro cell. Implementing energy-efficient power controls for small cells based on real-time traffic, rather than prediction models, will shift the network from "always on" to "always available."

106. **Need to improve the base station power efficiency:** Base stations are the least energy-efficient components of networks, and are a dominant source of power consumption. Excessive base station power is escalating because of the reduced efficiency of RF amplification in higher frequency bands. In order to combat this problem, we need to develop new Massive MIMO radios with low-gain antennas and integrated circuits with cooling techniques and implement energy-optimal control feedback loops informed by analytics on system resources.

107. **Need to improve coordination between the converging energy and telecommunications industry for better grid utility:** Network densification poses a further strain on the grid/utility system, because it must deliver more power to an increasingly complex network, and guarantee network reliability which is required by NextG applications. Also, network-connected devices require additional computing power to activate the network interface and participate in the network.

108. **Need to study smart green systems that include inter-computing and service execution between different systems:** This programmable system is based on a single, unifying controllability framework spanning all resources a tenant is authorized to control, including from previously separate and heterogeneous domains, e.g., enterprise and telecommunications networks, virtual and physical, data centers and routers, satellites, and terrestrial nodes, etc. The unifying controllability framework will glue the disparate resource islands to one system of the tenant supporting smart flexible instantiation and adaptive, elastic, and correct execution of any service on the resources.

# Appendix A: Works Cited

NIST consulted a significant number of communications industry R&D publications while preparing this report and supporting working Group meetings. NIST reviewed the following publications throughout the stakeholder engagement process to ensure the gaps described in this report complement rather than overlap with similar R&D planning efforts. NIST appreciates the time, resources, and expertise report contributors used to produce this list of reference materials, and welcomes external feedback on how the NIST R&D Gaps Report aligns with the activities of other research organizations.


1. Nada Golmie, David Cypher, Marc Leh, Darcy Ziegler (2018) Future Generation Wireless Research and Development Gaps Report. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 1219. https://doi.org/10.6028/NIST.SP.1219, p.01
2. "H.R.6395 - 116th Congress (2019-2020) William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021." Congress.gov, Library of Congress, 1 January 2021. https://www.congress.gov/bill/116th-congress/house-bill/6395, p.03
3. U.S. Department of Defense (2023) National Defense Science & Technology Strategy 2023. (U.S. Department of Defense, Washington D.C.). Retrieved from https://media.defense.gov/2023/May/09/2003218877/-1/-1/0/NDSTS-FINAL-WEB-VERSION.PDF, p.04
4. SRC (2021) Decadal Plan for Semiconductors. Retrieved from https://www.src.org/about/decadal-plan/decadal-plan-full-report.pdf, p.04
5. SRC (2021) Decadal Plan for Semiconductors. Retrieved from https://www.src.org/about/decadal-plan/decadal-plan-full-report.pdf, p.05
6. NIST (2022) Strategic Opportunities for U.S. Semiconductor Manufacturing. (U.S. Department of Commerce, Washington, D.C.), NIST CHIPS Series Report 1000, 1st Ed., Vol. 1. Available at: https://doi.org/10.6028/NIST.CHIPS.1000, p.05
7. NIST (2022) CHIPS for America Strategy. (U.S. Department of Commerce, Washington, D.C.). Available at: https://www.nist.gov/document/chips-america-strategy, p.05
8. *CHIPS and Science Act 2022 Division Summary* (2022) Senator Chris Van Hollen. https://www.vanhollen.senate.gov/download/chips-and-science-act-of-2022-summary&download=1, p.08
9. NSF (2023) CHIPS and Science. Retrieved from https://new.nsf.gov/chips, p.08
10. NIST (2023) A Vision and Strategy for the National Semiconductor Technology Center. (U.S. Department of Commerce, Washington, D.C.). Available at: https://www.nist.gov/document/vision-and-strategy-national-semiconductor-technology-center, p.08
11. "Text - H.R.1319 - 117th Congress (2021-2022): American Rescue Plan Act of 2021." Congress.gov, Library of Congress, 11 March 2021. https://www.congress.gov/bill/117th-congress/house-bill/1319/text, p.09
12. NIST (2023) Wireless Spectrum Research & Development (WSRD) https://www.nist.gov/news-events/events/2023/05/wsrd-workshop-making-data-available-national-spectrum-management, p.10
13. NSF (2021) Resilient Intelligent Next Generation Systems. Retrieved from https://www.nsf.gov/pubs/2021/nsf21581/nsf21581.htm, p.10
14. NSF (2022) Technology, Innovation, and Partnerships. Retrieved from https://beta.nsf.gov/tip/latest, p.10
15. NSF (2022).Future of Semiconductors. https://beta.nsf.gov/funding/opportunities/national-science-foundation-future-semiconductors, p.10
16. NSF (2023) AI Institute for Future Edge Networks and Distributed Networks (AI Edge) https://live-aiedge-program.pantheonsite.io/, p.10
17. NSF (2023) Spectrum Innovation Initiative. Retrieved from https://www.nsf.gov/mps/oma/spectrum_innovation_initiative.jsp, p.10
18. NSF (2023) Platforms for Advanced Wireless Research (PAWR) https://advancedwireless.org/, p.10

19. NSF/Intel (2019) Partnership on Machine Learning for Wireless Networking Systems (MLWiNS) https://www.nsf.gov/pubs/2019/nsf19591/nsf19591.htm, p.10
20. NIST (2023) NIST Generative AI Public Working Group. Retrieved from https://www.nist.gov/news-events/news/2023/06/biden-harris-administration-announces-new-nist-public-working-group-ai, p.10
21. NIST (2023). NextG Channel Model Alliance. Retrieved from https://nextg.nist.gov/, p.10
22. NIST (06/29/2022) NextG Wireless R&D Gap Analysis Workshop, Joint Communications and Sensing (U.S. Department of Commerce, Washington, D.C.), p.11
23. NIST (05/04/2022) NextG Wireless R&D Gap Analysis Workshop, Hardware and Higher Frequencies (U.S. Department of Commerce, Washington, D.C.)., p.13
24. Semiconductor Research Corporation (SRC) Joint University Microelectronics Program (JUMP). Retrieved from https://www.src.org/program/jump2/, p.13
25. FCC Notice of Inquiry and Order (2022) "Expanding Use of the 12.7-13.25 GHz Band for Mobile Broadband or Other Expanded Use," https://docs.fcc.gov/public/attachments/FCC-22-80A1.pdf, p.21
26. FCC Notice of Inquiry (2022) "Promoting Efficient Use of Spectrum through Improved Receiver Interference Immunity Performance." https://docs.fcc.gov/public/attachments/FCC-22-29A1.pdf, p.21
27. FCC Technological Advisory Council (2022) Recommendations to the Federal Communications Commission Based on Lessons Learned from CBRS. https://www.fcc.gov/sites/default/files/recommendations_to_the_federal_communications_commission_based_on_lessons_learned_from_cbrs.pdf, p.21
28. Networking and Information Technology Research and Development (2022) Advanced Wireless Test Platforms Team Information Request Report. https://www.nitrd.gov/pubs/AWTP-Info-Request-Report-2022.pdf, p.23
29. NSF (2023) Platforms for Advanced Wireless Research. Retrieved from https://advancedwireless.org/, p.23
30. NIST (06/09/2022) NextG Wireless R&D Gap Analysis Workshop, Joint Communications and Sensing (U.S. Department of Commerce, Washington, D.C.), p.25
31. Ericsson (2022) "Ericsson Mobility Report." https://www.ericsson.com/4ae28d/assets/local/reports-papers/mobility-report/documents/2022/ericsson-mobility-report-november-2022.pdf, p.32
32. SRC (2021) Decadal Plan for Semiconductors. Retrieved from https://www.src.org/about/decadal-plan/decadal-plan-full-report.pdf, p.32
33. NIST (08/03/2022) NextG Wireless R&D Gap Analysis Workshop, Data Availability, Use, and Privacy (U.S. Department of Commerce, Washington, D.C.), p.32
34. NIST (2022). NIST Data Privacy Framework. (U.S. Department of Commerce, Washington, D.C.), Available at: https://www.nist.gov/privacy-framework, p.35
35. NIST (2022) NextG Wireless R&D Gap Analysis Workshop, Data Availability, Use, and Privacy (U.S. Department of Commerce, Washington, D.C.), Available at:https://www.nist.gov/ctl/wirelessnet/nextg-wireless-rd-gap-analysis, p.36
36. NIST (2022) Post Quantum Cryptography Workshop. (U.S. Department of Commerce, Washington, D.C.). Available at: https://csrc.nist.gov/Projects/post-quantum-cryptography/workshops-and-timeline, p.39
37. Marco Giordani, and Michele Zorzi, (2021) Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities IEEE Network, vol. 35, no. 2, pp. 244– 251. https://ieeexplore.ieee.org/document/9275613, p.44
38. John Meredith, Joern Krause, Patrick Merias (2019) Study on New Radio (NR) to support non-terrestrial networks. (3GPP) (Release 15), TR 38.811. https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3747, p.46

# Appendix B: Additional Resources

The following research materials informed the stakeholder engagement and report writing activities for this effort.


39. IEEE International Network Generations Working Group (2022) IEEE International Network Generations Roadmap. IEEE 2022 Edition. https://futurenetworks.ieee.org/roadmap
40. NEXT G Alliance: an ATIS Initiative (2022) NextG Alliance Report: Roadmap to 6G. Alliance for Telecommunications Industry Solutions. https://nextgalliance.org/wp-content/uploads/2022/02/NextGA-Roadmap.pdf
41. Thyaga Nandagopal (2021) A Vision for NextG Networks and Systems: a view from the National Science Foundation. (National Science Foundation, Alexandria, VA).
42. NGMN Alliance (2021) 6G Drivers and Vision. Next Generation Mobile Networks. https://www.ngmn.org/wp-content/uploads/NGMN-6G-Drivers-and-Vision-V1.0_final.pdf
43. The 5G Infrastructure Association Vision and Societal Challenges Work Group (2021) European Vision for the 6G Network Ecosystem. The 5G Infrastructure Public Private Partnership. https://5g-ppp.eu/white-paper-by-the-5g-ia-vision-and-societal-challenges-working-group
44. Horizon 2020, Hexa-X, 5G PPP (2021) AI-driven Communication & Computation Co-design: Gap Analysis and Blueprint. Hexa-X Consortium. https://hexa-x.eu/wp-content/uploads/2021/09/Hexa-X_D4.1_slideset.pdf
45. IEEE 5G (2017) IEEE 5G and Beyond Technology Roadmap White Paper. IEEE. https://futurenetworks.ieee.org/roadmap/roadmap-white-paper
46. Yifei Yuan, Yajun Zhao, Baiqing Zong, Sergio Parolari (2020) Potential Key Technologies for 6G Mobile Communications. Science China Information Sciences, 63(8): 18330.1. https://doi.org/10.1007/s11432-019-2789-y
47. Harsh Tataria, Mansoor Shafi, Andreas F. Molisch, Mischa Dohler, Henrik Sjöland, Frederick Tufvesson (2021) 6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities. IEEE 109(7): 1166-1199. https://ieeexplore.ieee.org/iel7/5/9460558/09390169.pdf
48. 5GIC Strategy Advisory Board (2021) 6G Wireless: A New Strategic Vision. University of Surrey.https://www.surrey.ac.uk/sites/default/files/2020-11/6g-wireless-a-new-strategic-vision-paper.pdf
49. Ian F. Akyildiz, Chong Han, Zhifeng Hu, Shuai Nie, Josep M. Jornet (2021) TeraHertz Band Communication: An Old Problem Revisited and Research Directions for the Next Decade. IEEE Transactions on Communications 70(6), 4250-4285. https://arxiv.org/pdf/2112.13187
50. NetWorld2020, E. T. P. (2020) Smart Networks in the context of NGI. Strategic Research and Innovation Agenda 2021, 27, 1-240. https://www.networldeurope.eu/wp-content/uploads/2018/11/networld2020-5gia-sria-version-2.0.pdf?x91731
51. Special Competitive Studies Project (2022) Mid-Decade Challenges to National Competitiveness. Special Competitive Studies Project. https://www.scsp.ai/wp-content/uploads/2022/09/SCSP-Mid-Decade-Challenges-to-National-Competitiveness.pdf
52. CHIPS Act of 2022 Pub. L. No. 116-283, § 10201-10235, 281, 321 Stat. 281 (2022).
53. Jacob Hoydis Faycal Ait Aoudia, Alvaro Valcarce, Harish Viswanathan (2021) Toward a 6G AI-Native Interface. IEEE Communications Magazine. https://doi.org/10.48550/arXiv.2012.08285
54. Dong, Rongkang, Yuyi Mao, and Jun Zhang. "Resource-Constrained Edge AI with Early Exit Prediction." Journal of Communications and Information Networks 7.2 (2022): 122-134. https://ieeexplore.ieee.org/abstract/document/9815196/
55. Report from the FCC TAC on Advanced Spectrum Sharing, https://www.fcc.gov/sites/default/files/fcc_tac_meeting_slides_12-08-2022-final.pdf
56. Draft National Strategy on Microelectronics Research (for Public Comment). https://www.whitehouse.gov/wp-content/uploads/2022/09/SML-DRAFT-Microlectronics-Strategy-For-Public-Comment.pdf

57. Latva-aho, M., & Leppänen, K. (2019). Key Drivers and Research Challenges for 6G Ubiquitous Wireless Intelligence. 6G Research Visions 1. https://www.6gflagship.com/key-drivers-and-research-challenges-for-6g-ubiquitous-wireless-intelligence/ Matinmikko-Blue
58. M., Aalto, S., Asghar, M. I., Berndt, H., Chen, Y., Dixit, S., ... & Öörni, A. (2020). White paper on 6G drivers and the UN SDGs. 6G research visions, no. 2. https://www.6gflagship.com/white-paper-on-6g-drivers-and-the-un-sdgs/
59. Ali, S., Saad, W., & Steinbach, D. (2020). White Paper on Machine Learning in 6G Wireless Communication Networks. 6G Research Visions, No. 7. https://www.6gflagship.com/white-paper-on-machine-learning-in-6g-wireless-communication-networks/
60. Ylianttila, M., Kantola, R., Gurtov, A., Mucchi, L., Oppermann, I., Yan, Z., ... & Röning, J. (2020). 6G white paper: Research challenges for trust, security and privacy. 6G research visions, no. 9. https://www.6gflagship.com/6g-white-paper-research-challenges-for-trust-security-and-privacy/
61. Pärssinen, A., Alouini, M. S., Berg, M., Kürner, T., Kyösti, P., Leinonen, M. E., ... & Wambacq, P. (2021). White paper on RF enabling 6G: opportunities and challenges from technology to spectrum. 6G research visions, no. 13. https://www.6gflagship.com/white-paper-on-rf-enabling-6g-opportunities-and-challenges-from-technology-to-spectrum/

# Acknowledgments


The contributions of the volunteer working group members were pivotal to the formulation of the insights and conclusions presented in this report. NIST greatly appreciates their dedication, expertise, and support of this effort.

| | |
|---|---|
| Gerald Adams | SpaceX |
| Valerie Arsenault | Robert Half Consulting |
| Mehdi Bennis | University of Oulu, Finland |
| Eric Burger | Virginia Tech |
| Ranveer Chandra | Microsoft |
| John Chapin | National Science Foundation |
| Kaushik Chowdhury | Northeastern University |
| Claudio Da Silva | Meta Platforms |
| Colin Daly | Corning |
| Jameson Dempsey | SpaceX |
| Falko Dressler | TU Berlin |
| Jinfeng Du | Nokia |
| Gerhard Fettweis | TU Dresden |
| Tim Forde | SRS |
| Ana Garcia Armada | Universidad Carlos III de Madrid, Spain |
| Nuria Gonzalez Prelcic | North Carolina State University |
| Amitava Ghosh | Nokia |
| Monisha Ghosh | University of Notre Dame |
| Erwin Gianchandani | National Science Foundation |
| Marco Giordani | University of Padova |
| Abhimanyu Gosain | Northeastern University |
| Fred Harris | University of California San Diego |
| Robert Heath | North Carolina State University |
| Waguih Ishak | Corning |
| Lin Jenshan | National Science Foundation |
| Josep Jornet | Northeastern University |
| Ali Khayrallah | Ericsson |
| Matti Latva-aho | University of Oulu, Finland |
| Naomi Lefkowitz | National Insititute of Standards and Technology |
| Clara Li | Intel |
| Joseph Lipowski | Starry, Inc. |
| Dora Lopez | The University of Oklahoma |
| Upamanyu Madhow | University of California Santa Barbara |
| Pres Marshall | Google |
| Thomas Marzetta | New York University |
| Muriel Medard | Massachussets Institute of Technology |
| Tommaso Melodia | Northeastern University |
| Daniel Mittleman | Brown University |
| Andreas Molisch | University of Southern California |
| Edward Oughton | George Mason University |
| Aarno Pärssinen | University of Oulu, Finland |
| Guru Parulkar | Open Networking Foundation (ONF) / Stanford University |

| | |
|---|---|
| Petar Popovski | Aalborg University |
| Chris Ramming | VMware |
| Dipankar Raychaudhuri | Rutgers University |
| Gabriel Rebeiz | University of California San Diego |
| Jeff Reed | Virginia Tech |
| Jennifer Rexford | Princeton University |
| Tom Rondeau | Department of Defense OUSD R&E |
| Sumit Roy | University of Washington |
| Henning Schulzrinne | Columbia University |
| Meryem Simsek | Nokia Bell Labs |
| Tod Sizer | Nokia Bell Labs |
| Alex Sprintson | Nokia Bell Labs |
| Paul Sutton | SRS |
| Shilpa Talwar | Intel Corporation |
| Rath Vannithamby | Intel Corporation |
| Deepak Vasisht | University of Illinois Urbana-Champaign |
| Dinesh Verma | IBM TJ Watson Research Center |
| Harish Viswanathan | Nokia |
| Joerg Widmer | IMDEA Networks |
| Charlie Zhang | Samsung |
| Gordon Zhang | Interdigital |
| Wang Zhengdao | George Mason University |
| Michele Zorzi | University of Padova |

NIST COMMUNICATIONS TECHNOLOGY LABORATORY