NEXT G ALLIANCE
an ATIS initiative

Next G Alliance Report:

Roadmap to 6G

February 2022

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Foreword

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

ATIS is accredited by the American National Standards Institute (ANSI). ATIS is the North American Organizational Partner for the 3rd Generation Partnership Project (3GPP), a founding Partner of the oneM2M global initiative, a member of the International Telecommunication Union (ITU), as well as a member of the Inter-American Telecommunication Commission (CITEL). For more information, visit www.atis.org. Follow ATIS on Twitter and on LinkedIn.

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

Contents

1 Introduction

1.1 Scope

The scope of this "Next G Alliance Report: Roadmap to 6G" is to provide a foundational vision for 6G that addresses both North American needs and global alignment goals and to develop priorities and strategies for achieving North American leadership alongside other regions' leadership. This includes describing the key challenges across social and economic, technical, spectrum, applications, and sustainability (e.g., energy, environmental) considerations, and recommending governmental actions and standardization strategies.

This first release of the report describes the Next G Alliance foundational vision and roadmap in terms of key goals and objectives, the timeline of major milestones on the path to 6G, and key priorities and recommendations that reflect work across the Next G Alliance. The findings and recommendations will be updated in future releases, along with additional content that supports the overall scope of the report.

1.2 About Next G Alliance

The Next G Alliance is a bold new initiative to advance North American wireless technology leadership over the next decade through private sector-led efforts in association with government stakeholders. With a strong emphasis on technology market-readiness, the work will encompass the full lifecycle of research and development, manufacturing, standardization, and market readiness.

The Next G Alliance is currently comprised of a six working groups, a Steering Group, and a Full Members group, as shown in Figure 1.1. The Full Members group is the top-level group responsible for strategy, operating procedures, and membership. The Steering Group oversees the implementation of the strategic direction by defining working groups. The working groups identified in the figure are contributing members to this Roadmap Report. In addition, there is a Technical Program Office that coordinates operations across the organizational structure.

> The Next G Alliance's "Roadmap to 6G" report is a private sector-led initiative to outline a vision for 6G and a roadmap that addresses North America's imperatives.

The National 6G Roadmap Working Group is responsible for integrating the results from each working group and formulating a cohesive vision, roadmap, and timeline. This effort is intended to be a reference to drive North American leadership across industry, academia, and government stakeholders in order to meet following Next G Alliance objectives:

- Create a Next G development roadmap that will promote a vibrant marketplace for 6G introduction, adoption, and market-readiness with North American innovation in mind.
- Develop a set of national priorities that will influence government applied research funding and promote incentivized government actions.
- Progress North America's ecosystem to promote development across the full lifecycle of research to realization, aligned with commercialization outcomes.

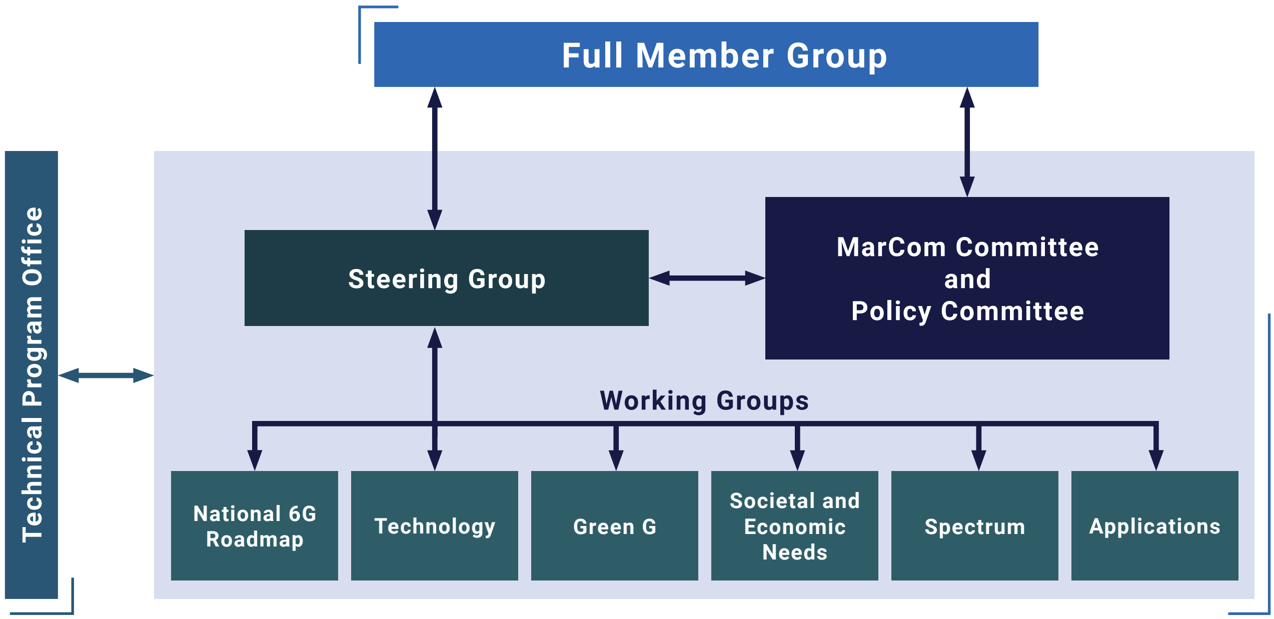


Figure 1.1: Next G Alliance Organizational Structure

2 Partnering with Government

The Next G Alliance brings together diverse segments of the industry, academia, and government. Ensuring North American leadership in wireless technology across key sectors will strengthen and promote the region's economic interests globally. The work of the Next G Alliance is critical and timely because wireless technology underpins the advancement of several important industries. These include aerospace, agriculture, defense, education, health care, manufacturing, media, energy, transportation, public safety, and many others, all of which are vital to North American governments' interests and increasingly depend on wireless technology.

Ensuring North American leadership in 6G technologies across key consumer and industrial sectors will promote and strengthen the region's economic interests, both locally and globally.

To be successful, the Next G Alliance will need to reflect a North American model in both approach and results. Unlike some regions of the world, industry will lead the research, development, and commercialization of 6G in North America. However, the government will play an important role in advancing and supporting these efforts through policy and partnership.

There are at least three key areas where government support is necessary to promoting North American leadership in 6G and beyond:

- » Government policymakers and industry need to work hand-in-hand to establish a vision for North American 6G leadership, and then construct policy frameworks that will support industry innovation. This includes coordinating with other partner nations sharing similar goals to achieve consistent policy priorities, where possible, that will create a stronger economic base consistent with these shared goals.
- » In order to ensure that these shared North American policy priorities are designed into the fabric of 6G, government must support domestic research and development proactively. Similar efforts have already begun in earnest in other regions of the world—including heavily funded and government-directed efforts by our largest economic competitors. Government support will be necessary to compete with these other efforts, including funding of research and tax incentives for industry R&D.
- » Government needs to begin the process of implementing policies that incentivize and promote public and private investment in commercialization and deployment of next-generation wireless technologies. Although 6G will likely not be ready for market until the turn of the decade, government action to ensure that North America leads in this effort—such as making available adequate and appropriate spectrum—needs to start now in order to meet that timeline.

The specific priorities within these areas will necessarily evolve over the next several years as the 6G developmental lifecycle matures. For purposes of this early roadmap vision, however, the Next G Alliance has identified these three key areas for government support for the mission of North American 6G leadership.

2.1 Creating a North American Vision for 6G Success

The next generation of wireless technology will be woven into the daily lives of society to an even greater degree than today's technology. As identified throughout this report, this role presents tremendous opportunities for 6G to facilitate key public policy objectives in areas such as security, privacy, environment, safety, health, sustainability, and equity, among others. But a policy framework that provides clarity to the industry, balanced with the flexibility necessary to promote competition in innovation, will be critical to create a foundation for key 6G applications and use cases.

Successful implementation of this vision must include an effort to work with other market-driven partners on common approaches to key policy issues to the extent possible. The very nature of advanced communications technologies facilitates the ability to offer services and social benefits across borders. Identifying areas for consistent societal, legal, and regulatory regimes will enable 6G technologies to achieve their full potential. Additionally, agreement on approaches will promote greater leverage in support of those positions within international bodies establishing standards for 6G.

2.2 Supporting a Research and Development Agenda for 6G Leadership

Various countries and regions have already announced formal plans of government support for their research and development efforts that will define 6G. They all have the goal of firmly establishing themselves as the epicenter for the next generation of innovation and economic growth. A North American initiative led by industry and with support from government will be essential for balancing the efforts of these other regions and ensure North American 6G leadership.

Government, industry, and academia will need to cooperate more closely than we traditionally have in identifying research priorities. This should begin with a concerted effort by industry, academia, and government to develop a research agenda for North American 6G leadership in areas of shared interest. Specifically, the Next G Alliance invites government stakeholders to join our industry and academic members to engage in a dialogue identifying mutual 6G research priorities.

To successfully compete with the aggressive efforts of other countries, North American governments must provide resources to support industry-led, domestic-based research. Such support would include:

- Direct financial support and industry tax incentives for basic research.
- Access to government test bed facilities.
- Bridging the gap between research and development to promote adoption of early-stage technologies.

2.3 Creating a Foundation for Investment in North American 6G Leadership

Competing with other regions of the world to lead in 6G will require policies that establish the necessary building blocks for private sector investment in the research, development, and deployment of 6G networks. While the next generation of wireless networks will build upon ongoing work to support 5G networks, achieving the goal of 6G leadership will pose additional challenges in areas such as spectrum needs, manufacturing base, workforce skilling, and infrastructure deployment. Recognizing that these foundations take time to establish, one of the primary missions of the Next G Alliance is to bring industry, government, and academia to the table to begin working on these policies much earlier in the innovation lifecycle than has been done for previous generations.

> While industry along with academia will lead 6G research, development, and commercialization activities in North America, government will play an important role through policy, incentivization, and partnership.

3 North American 6G Vision

Next G Alliance's six audacious goals describe North America's priorities and ambitions for 6G systems.

The International Mobile Telecommunications (IMT) systems for 2030 and beyond will be developed as a global standard to better serve the communication needs in every continent of the world. The Next G Alliance has identified six audacious goals that describe top priorities for North America's contribution and leadership in these future global standards, deployments, products, operations, and services. These priorities contemplate both the societal and economic needs across North America, and the technology strengths that North America will contribute to the rest of the world. The foundation of Next G Alliance's 6G Vision is established by our audacious goals and the key research priorities covered in Sections 5 through 9 of this report. This section describes the six goals that are listed below and depicted in Figure 3.1.

1. **Trust, Security, and Resilience** should be advanced such that future networks are fully trusted by people, businesses, and governments to be resilient, secure, privacy preserving, safe, reliable, and available under all circumstances.

2. An enhanced **Digital World Experience** consists of multi-sensory experiences to enable transformative forms of human collaboration, as well as human-machine and machine-machine interactions that will transform work, education, and entertainment, thereby improving quality of life and creating great economic value.

3. **Cost Efficient Solutions** should span all aspects of the network architecture, including devices, wireless access, cell-site backhaul, overall distribution, and energy consumption. These must be improved for delivering services in a variety of environments, including urban, rural, and suburban, while also supporting increased data speed and the services that are expected for future networks.

4. **Distributed Cloud and Communications Systems** built on virtualization technologies will increase flexibility, performance, and resiliency for key use cases such as mixed reality, URLLC applications, interactive gaming, and multi-sensory applications.

5. An **AI-Native Network** is needed to increase the robustness, performance, and efficiencies of wireless and cloud technologies against more diverse traffic types, ultra-dense deployment topologies, and more challenging spectrum situations.

6. **Sustainability** related to energy efficiency and the environment must be at the forefront of decisions throughout the life cycle, toward a goal of achieving IMT carbon neutral by 2040. Advances will fundamentally change how electricity is used to support next-generation communications and computer networks, while strengthening the role that information technology plays in protecting the environment.

3.1 Framework for a North America 6G Vision

The Next G Alliance aims to engage a diverse ecosystem consisting of operators, vendors, hyperscalers, research groups, universities, and government representatives. The stakeholders within the scope of the Next G Alliance audience include policymakers, government leadership, application developers in vertical markets, research scientists, engineers, and more. In order to describe our 6G vision to such a diverse audience, the framework shown in Figure 3.2 is used to address stakeholders at multiple levels.

Figure 3.1: Next G Alliance Six Audacious Goals

» National Imperatives: We describe the societal, economic, and governmental factors that drive each objective. To set a bold and clear vision, we describe the change that will be realized with 6G compared to 5G and describe the unique needs and leadership opportunities from a North American perspective.

» Applications and Markets: We describe the key markets and use cases enabled by realizing the vision and consider co-dependencies with adjacent industries and groups.

» Technology Development: We identify the new technology areas that are needed to achieve success of each objective and explain why these objectives cannot be achieved with 5G technologies alone. Key performance indicators are also identified to set success criteria for technology objectives.

Goal #1: Trust, Security, and Resilience

The 6G system will be trusted by people, businesses, and governments to be resilient, secure, privacy preserving, safe, reliable, and available under all circumstances.

3.2 Trust, Security, and Resilience

6G will influence biological, physical, and virtual processes by increasing the acceleration of digital transformation across society. The engines of transformation established by 3G and 4G enabled the exponential increase of bandwidth in networks, the expansion of coverage across all users, and the ability to handle mobility and service continuity across the internet for telecommunications and information services. The importance of networks in society is clear today, and in the 2030s their role will be even more critical. Users and our societies expect a network on which they can depend on and trust under all circumstances. This largely means a system that is reliable, resilient, and secures communication and information.

By 2030, consumers will have additional expectations for almost all everyday activities, raising user and societal needs for dependable and trustworthy networks.

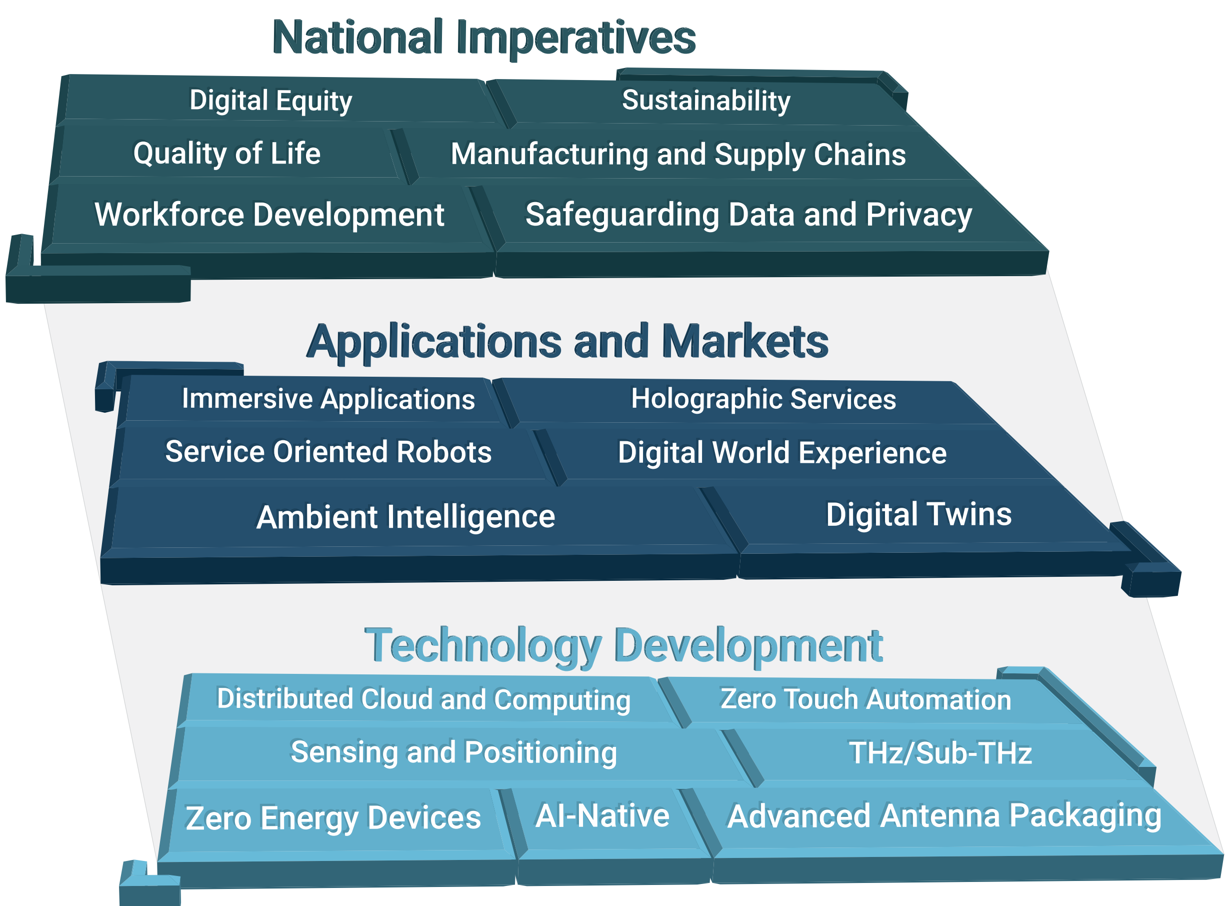


Figure 3.2: Three-Level Framework for Next G Alliance 6G Vision

Rapid 6G innovation will rely on ethical use of technology, data privacy, and a framework for secure technology sourcing and supply-chains.

New features, use cases, and technologies expected to be employed by 6G pose new security challenges, as so the vastly expanded attack surfaces created by the burgeoning number of devices connected to 6G networks. The applicability of 6G in many critical applications puts much more demanding requirements on dependability, resilience, attack resistance, detection, and mitigation than in previous generations. Use of 6G for both sensing and communication will affect user privacy. The integrated use of AI and distributed edge cloud systems require ways to ensure data is managed safely and guarantees that processing was performed in accordance with legal and regulatory compliance frameworks. Where relevant, data under control of the 6G network must moreover be used ethically, especially when processed by AI modules to serve applicable objectives. Ethical use would ensure that data provenance is maintained, and that data use respects ownership, privacy, and dignity. Also, data confidentiality related to an individual and proprietary ownership must be maintained. Furthermore, if the data is used to create AI models, it must be with consent for the specific use and utilized in a manner that does not introduce any bias in the inference. In 6G, security and trust should improve on the palpable achievements of 5G. All aspects of the network, from securing the supply chain to component design and integration, will incorporate aspects to address security and privacy to elevate the consumer's trust in the network. 6G networks will be more resilient and responsive to attacks and outages, resulting in higher degrees of dependability and availability.

3.2.1 National Imperatives

North American governments have expressed concerns about the dependence of the semiconductor and manufacturing value chain on limited sources of supply. Various government agencies and departments, including the military, are considering increased use of commercial technologies to meet their own ICT needs. There is a perception that open interfaces and open-source implementations of software will mitigate some of the risks that have been identified, while offering avenues for greater competition from more diverse solution providers. Clearly, there must also be greater attention paid to establishing supply chain security with well-integrated network solutions.

3.2.2 Applications and Markets

Trustworthiness is derived from confidence that a system will perform as expected and is based on many factors that are not technological in nature. While trustworthiness itself is not characterizable with purely technical solutions, it is possible to follow certain practices that will provide evidence of the ability of a system (e.g., a network or a service) to meet expectations about its reliability, security, safety, and availability. The relation of technological cycles to resilient system design is illustrated in Figure 3.3. Trust in technologies is greatly aided by offering evidence of security and performance across the entire product cycle. Resilience addresses the ability of the system to anticipate, respond, and react to disturbances, errors, faults, and threats.

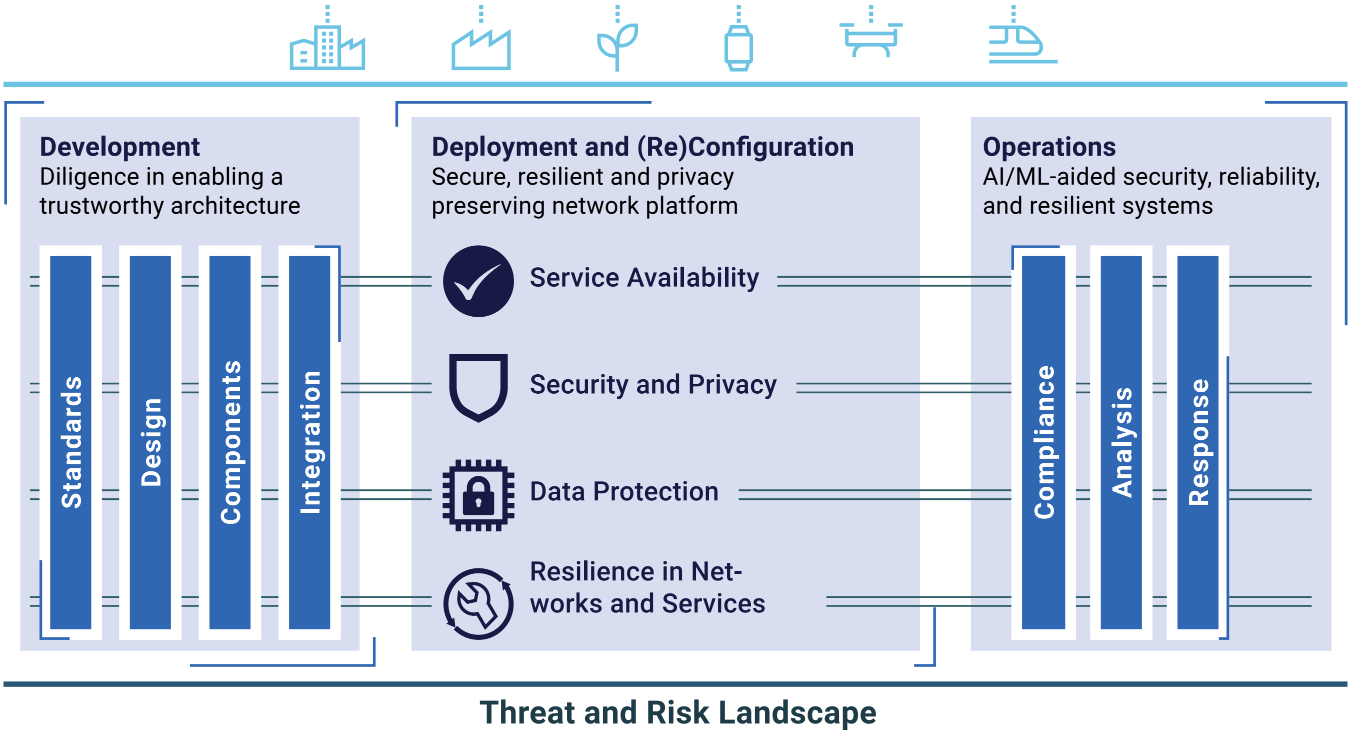


Figure 3.3: The Relation of Technological Cycles to Resilient System Design

The figure illustrates four key objectives in proving that a network can be trusted. These objectives can be realized only if the entire generational lifespan of the network attends to requirements for each service, including development, deployment, configuration and release, and operations:

1. **Service availability:** The 6G system and future generations should be designed to assume more critical roles in industry and society.

2. **Security and privacy:** A significant difference between 5G Advanced and 6G will be the availability of user-programmable behavior in networks, especially in edge clouds where proprietary or personal information is likely to be exposed to underlying computational systems.

3. **Data protection:** Protecting data not just in transit but also at rest and in use is important.

4. **Resilience in networks and services:** A large part of resilience in networks arises from the ability to meet performance objectives that have diverse requirements within a single service. Services need novel approaches to recovery from disturbances and denial of service (DoS) attacks that attempt to compromise the availability, integrity, or security of the network, as well as from faults and errors caused by equipment failure or operational malfunction.

In addition to issues of network trustworthiness, 6G systems will encompass a broader set of components to deliver, for example, digital or enhanced experiences. This extends the requirements for trust, security, and resilience to include user devices, applications delivering enhanced experiences, and policies linked to the management of user data (e.g., interactions, stored profiles).

3.2.3 Technology Development

There are several dimensions to the challenge of addressing trust, security, and resilience goals. At the technical level, established practices exist for individual technology components based on experience with earlier network generations. 6G brings new challenges in the form of technical issues at a systems level, where many more interlinked technologies will be operating at much higher processing rates.

Greater observability of network and RAN metrics, along with well-defined relationships between producers and consumers of data, will improve the ability of the network to meet service requirements for internal and external objectives. Optimization objectives can be set for various machine learning workflows, such as service integrity, virtual machine isolation, real-time threat assessment based on changes in traffic characteristics, power consumption variations, initiation of resource redundancy, and automated adjustment of network configuration, to name a few. Service and network exposure functions can provide transparency to trusted interfaces, including internal consumers and external service components.

The Table 1 below lists technology enablers pertaining to trustworthiness, security, privacy, availability, and resilience.

Technology Challenges	Description	Technology Considerations
Service Availability	End-to-end observability is key to establishing KPIs that can form a composite measure of trustworthiness	Data pipeline for enhanced observability of RAN, cloud, core, and service metrics
	Resource allocation is an end-to-end problem that involves radio, compute, storage, and transport functionality	Efficient and robust resource provisioning for critical services
	Tracking and control of data and services through service exposure interfaces	Quality of service enhancements
Resilience	Use of data-driven techniques to assess the abilities, the limitations, and the operational state of the network toward each service; automated and dynamic methods of predicting and modifying network behavior to meet quality of experience	Network performance optimization
	Use of ML techniques for data-driven approaches to risk identification and mitigation to overcome vulnerabilities, faults, and disturbances	Threat detection and response
	Disaster relief and fault tolerance during crises	Local survivability
	Predictable and verifiable global supply chains, automated security operations, automated software generation, and validation using AI/ML	Automation in 6G
Trustworthy AI/ML	Explainable and ethical behavior from network-hosted AI models with auditing of service exposure to AI capabilities; privacy protection, and strong checks and balances on use of ML for lawful and ethical objectives	Explainable AI
	Data protection for third-party functionality, including confidential handling of datasets and model parameters for ML	Security and confidentiality for AI/ML
Security and Privacy	Chain of trust for all hardware and software components; techniques such as blind signatures, zero-knowledge proofs, and group signatures	Root-of-trust-based identities
	Protecting data in transit, at rest, and in use. Homomorphic encryption, multi-party computation, federated learning	Privacy-preserving technologies and protocol stacks
	Jamming detection and mitigation	Physical layer security
	Confidential computing for mission-critical network slices; use of trusted execution environments	Confidential computing
	Risk mitigation against the possible use of quantum computers to compromise traditional cryptographic method	Post-quantum cryptographic techniques
Observability and Resource Optimization	Continuous monitoring of observable and measurable metrics that can be analyzed with respect to compliance to key performance and security indicators	ML and data-analytic
	real-time prioritization of resources to achieve high levels of performance and resilience across peer-to-peer and device-to-network communication	Coverage solutions across all information and telecommunication services

Table 1: Technology Considerations for the Trust, Security, and Resilience Goal

3.2.3.1 Key Performance Objectives
Key performance objectives need to provide clear evidence of compliance with design and performance metrics. One possible model is the mechanisms used for security assurance. Assurance for a comprehensive trust model will include security assurance and will additionally incorporate other characteristics such as privacy, reliability, availability, and safety.

It is easier to provide security assurance and service availability assurance for more local deployments or controlled environments such as a factory floor or an industrial campus. Likewise, mission-critical public safety scenarios will benefit from good coverage across all information and telecommunication services. The overall objective in all these cases would be to make the network responsive to service requirements while being resilient against faults, disturbances, and threats. However, it is far more challenging to create assurance for an entire CSP network, or for services like C-V2X that depend on high reliability and availability across a wide coverage area. Assurance methodologies typically depend on an attestation of compliance to specifically designed requirements. An approach must be developed for assurance that accommodates the broadest range of deployments and use cases. It is expected that ML and data-analytic techniques will play an important role in generating the metrics that can improve assurance by means of real-time visibility into key states of the 6G system.

Goal #2: Digital World Experience

The 6G system will support multi-sensory experiences to enable transformative forms of human collaboration, as well as human-machine and machine-machine interactions that bring life-improving use cases and create new economic value.

3.3 Digital World Experience
6G Digital World Experiences (DWEs) encompass a variety of multi-sensory experiences that transform human interactions across physical, digital, and biological worlds. Innovative human-to-machine interfaces and synergies resulting from machine-machine communications are enablers of more expressive DWE interactions.

Inter-personal application DWEs can improve the quality of everyday living, (e.g., enabling emotive communications in friends or family interactions), quality of experience (e.g., enhancing shared experiences in multi-user gaming groups), or improve the quality of critical roles (e.g., humanized robotic care). By exploiting mixed reality representations, DWEs aim to allow people to appear anywhere at any time, intime, in any way they choose. Another example of a DWE that improves the quality of living or critical roles is when remote sensing, haptic feedback, and actuation are combined to enable extended reality (XR) interactions with distant or inaccessible objects. This might arise in cases of remote surgery or when an industrial technician cannot obtain hands-on access to repair a faulty machine.

> 6G Digital World Experiences extend reality across physical, digital, and biological worlds via multi-dimensional, multi-party, and multi-sensory techniques.

DWEs make these opportunities possible by re-shaping today's "flat-screen" approach with the addition of multi-dimensional, multi-party, and multi-sensory techniques. The commercial benefits in a future that combines mixed-reality with co-design include faster service innovation and shorter industrial-design cycles.

DWEs align with societal goals to modernize/maximize access to education and to enhance employment skills through affordable and easy-to-use technology. DWEs will add higher resolutions, new dimensions, and value to human interactions via life-improving applications that will be adopted broadly across society and support mass-market commercial models.

3.3.1 National Imperatives
North America has substantial expertise and leadership in cloud, computing, and communications technologies, which are foundational to 6G. Social media and enterprise IT businesses in North America are already experimenting with "metaverse" strategies, which share many of the cyber-physical, Internet of Senses and Tactile Internet characteristics associated with 6G DWEs. North American leadership in cloud computing provides a pathway to edge cloud technologies. Edge cloud approaches combine multiple sensor data streams at higher capacity and peak rates, from diverse sources for storage, retrieval, modeling, and rendering.

One national imperative is to initiate policies and programs to scale up and cross-pollinate North America's supply-side ecosystem for 6G DWEs. Broad funding of interdisciplinary research is crucial for DWEs. This implies a focus on next-generation network technology, as well as complementary technologies that lead to greater innovation and small/start-up business formation. There are ongoing congressional initiatives to strengthen leadership in immersive technology innovation.[1] If ultimately adopted, these efforts target billions of dollars in R&D, investment, and educational training for immersive technologies, AI, semiconductors, and advanced battery technology, among others. In order to enable the proliferation of immersive technologies, 6G should bring the wireless capability needed to support XR/AR/VR technology at

1 S.1260 - United States Innovation and Competition Act of 2021, *https://www.congress.gov/bill/117th-congress/senate-bill/1260*

scale. Other opportunities for synergy include the intersection of computing and communications, joint communications and sensing, and the internet and telecommunications domains.

Market adoption of the Internet demonstrated the pivotal role of government in setting "moonshot" goals and being a lead-user to support market-development. This suggests the potential for targeted, national initiatives to compress the intervals between research, technology demonstrators, adoption, and successive waves of new research.

3.3.2 Applications and Markets

There are several drivers of demand for DWEs, ranging from societal dynamics to economic developments. Work-from-home and de-urbanization patterns introduce new demands for remote collaboration going beyond the capabilities of screen interfaces. Physical distance in personal and professional settings affects the ease of communications and emotional well-being. In the industrial IoT (IIoT) domain, product innovation and supply-chain integration are two demand drivers. Finally, there are new imperatives arising from environmental sustainability concerns. Better use of technology can help to reduce unnecessary travel, wasted resources, and poor use of time.

There is also an economic rationale to support technology upskilling. Competitive pressures to improve productivity can be met via immersive approaches to education, life-long learning, and remote working. Affordable and accessible DWEs will bring disadvantaged and remote workers into the workforce.

6G DWEs are applicable across a variety of connected intelligence markets and use cases. The generic forms for initial applications are likely to involve immersive interpersonal communications, as well as the ability to perform complex multi-sensory and XR tasks remotely. Both forms are applicable to several markets including media, entertainment, and communications; interactive education; design and industrial automation; various approaches to health care and well-being; intelligent travel; transportation and utilities; and for government and national security.

3.3.3 Technology Development

The fundamental enabling framework for DWEs involves dynamic, multi-sensory, multi-layer representations of the physical world to implement digital twins or mirror worlds. Just as currently prevalent applications are built on multimedia foundations, future applications will rely on a merge of digital and physical worlds to create a wide variety of highly immersive experiences through deeper levels of human-computer interaction. These immersive experiences will underpin 6G systems and complementary technologies, e.g., innovative sensing, immersive XR, distributed inferencing, management, and intelligence computing, etc. The combination of these technologies is expected to yield human and machine experiences unthinkable with previous generations.

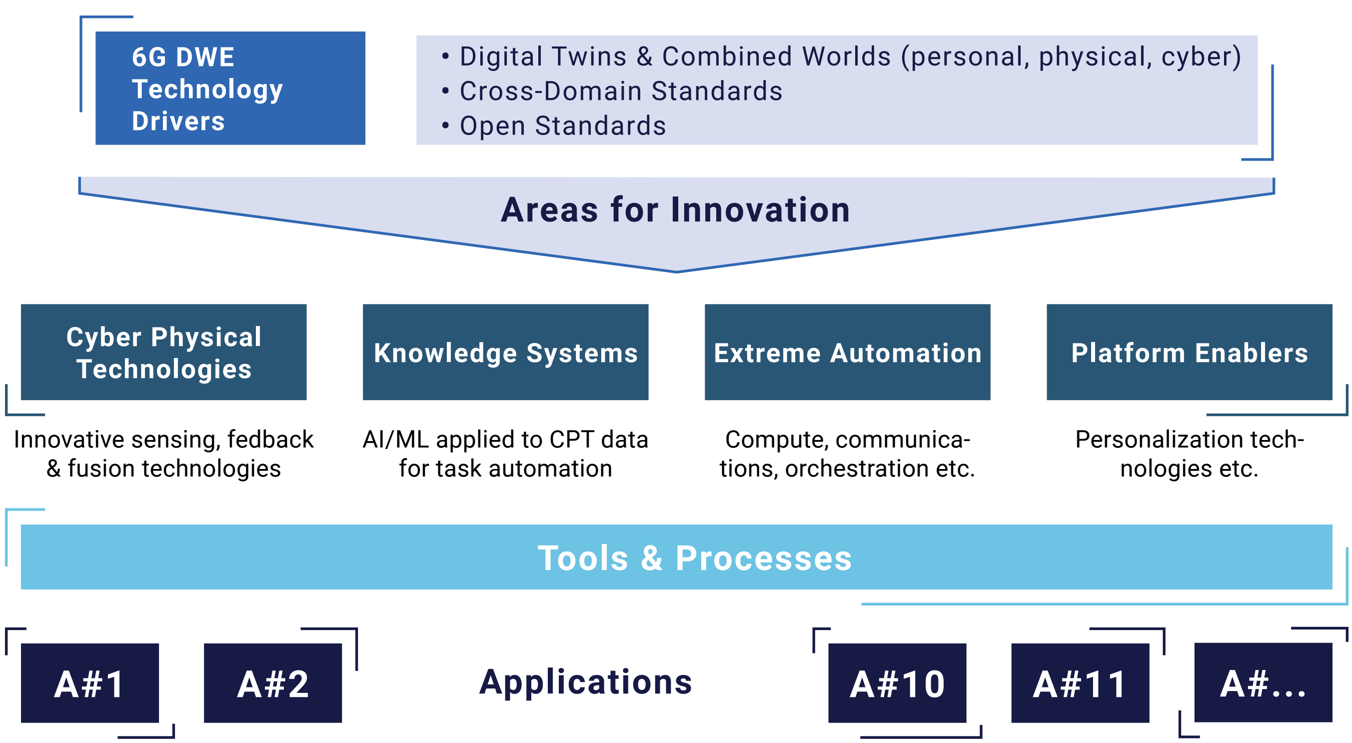


Figure 3.4: Factors Contributing to the Success of 6G DWEs

The cross-domain nature of 6G DWEs calls for open and interoperable standards that bring together several application and technology domains. Open standards enable interoperability and promote technology reuse, with attendant benefits for sustainability. They can also drive market scale, reducing the risk that DWEs end up as niche applications for a few mission-critical usage scenarios.

As Figure 3.4 shows, the translation of new 6G capabilities into viable DWE services depends on several factors. These include advances in at least four complementary technologies, the availability of processes and tools to simplify adoption, and market evangelization through highly visible, early applications.

The different technology challenges associated with DWEs depend on a new and wider set of technologies considerations as described in Table 2.

Technology Challenges	Description	Technology Considerations
Innovation in cyber-physical technologies	This involves the commingling of virtual/digital and physical worlds through innovative sensing and feedback approaches going beyond sight and sound.	» Innovation in point technologies (e.g., holographic communications, haptic interfaces). » Approaches to cross-technology fusion linking positioning/sensing and XR/haptics, as examples.
Development of knowledge systems technologies	The aim is to speed up intelligent data processing and task automation based on new, AI/ML techniques that assimilate and synthesize data from cyber-physical subsystems.	Design 6G systems with native AI/ML enablers (e.g., semantics) and tools (e.g., prediction models) to manage resources involved in delivering DWEs.
Enabling extreme automation technologies	Extreme automation applies to processing activities along the technology stack and service delivery chains with the aim of delivering intuitive and seamless digital experiences. This relies on a broad range of distributed computing and communications technologies that equip network operators to automate the dynamic orchestration of network resources, for example. Other examples apply to subscription and service activation tasks, masking complexity for end users, and the enforcement of more granular policies for privacy and security management.	Facilitate a greater reliance on dynamic, automation capabilities across communications, computing, device, interface, service enabler, and spectrum resources.
Provision of enabling tools and processes	» API and SDK enablers for developers to create innovative services from new 6G capabilities. » Consumer-protection controls and tools that users can rely on to trust and manage their digital world experiences.	Increase the availability and accessibility of tools for different user categories (e.g., 6G system operators, developers, consumer end users).
Evolution of computing and communications platform capabilities	These are horizontal enablers that are common to multiple use-case scenarios. They can apply to multi-user and multi-service-provider operating environments.	Development and deployment of personalization technologies (e.g., identity, handling of personal data).
Market creation based on showcasing enhanced applications and 6G capabilities	Applications that demonstrate the value of DWEs to the wider market, featuring combinations of various aspects of the family of 6G innovations.	» Service-oriented robots, combining ultra-high-speed data communications, simultaneous location, and mapping, with extreme automation. » Real-time personalization. » Merged-reality telepresence. » Immersive communications using XR and wearables.

Table 2: Technology Considerations for DWE Goal

3.3.3.1 Key Performance Objectives

The multi-faceted complexion of 6G DWEs means that several performance measures will be useful in gauging the progress of technological innovation and market development initiatives. The former includes metrics related to localization precision, 2D and 3D indoor sensing accuracy, range and velocity resolution, and object detection probability, among others.

Efforts to speed up the commercial adoption of DWEs introduce other interdependencies and should be viewed from an end-to-end perspective. There are at least three parts, beginning with a focus on cross-disciplinary research. The aim here is to expose standardized 6G capabilities in networks, compute fabric, and devices among the service provider and application developer communities and to adapt quickly to their feedback. Suitable measures of progress might focus on identifying 6G DWE capability requirements from application requirements and the extent to which applied research gains exposure in demand-side sectors outside of traditional ICT domains.

> Closer integration between compute and communications ecosystems offers many opportunities for North America to capitalize on DWE-market-development.

The second part focuses on solution engineering, with an emphasis on responsible engineering practices, to build user confidence and trust in 6G DWEs. This might involve measures to ensure the active involvement of ethics, digital rights, and data stewardship experts during the requirements-setting and standardization phases of 6G developments, for example.

The third and last step involves market creation through initiatives to showcase 6G DWE applications and to highlight commercialization opportunities. This would become evident through growing numbers of pilots and pre-commercialization trials involving solution providers working alongside demand-side organizations.

Goal #3: Cost Efficient Solutions

Cost Efficiency in all aspects of the network architecture including devices, wireless access, cell-site backhaul, overall distribution, and energy consumption must be improved for delivering services in a variety of environments, including urban, rural, and suburban, while also supporting increased data speed and services that are expected for future networks.

3.4 Cost-Efficient Solutions

The Next G Alliance recognizes that cost efficiency is foundational to the ubiquitous availability throughout North America of 6G networks and services. Some of the challenges associated with gaining cost efficiency are not unique to North America. However, it is important to note that North America represents a broad range of rural and urban environments, an industrial spectrum that includes sophisticated manufacturing and information services, agricultural enterprises, and disparate geography.

> Providing cost efficient coverage for urban, rural, and indoor environments, depends not only on deployed technologies, but also on innovations to business models and policies.

Cost efficiency may act as a catalyst for providing digital equity, which for subscribers can be defined as the satisfaction of three conditions: financial affordability, physical accessibility, and geographic availability of network services. Digital equity is further discussed in Section 5.1.1.

Enhanced Mobile Broadband (eMBB) is one of the core IMT-2020 services powering our digital lives and providing connectivity for innovative, high-rate, data-intensive applications. Semiconductor Research Corporation estimates that by 2032, there may be more than 1 million zettabytes (1^27 bytes) of data generated per year just from sensors.[2] The next generation of cellular networks must improve the efficiency of delivering the core cellular services, such as eMBB, in a variety of environments including urban, rural, and indoor.

> Cost efficiency is essential for affordable, accessible, and geographically widespread 6G networks and services throughout North America.

2 Semiconductor Research Corporation, "Interim report for the decadal plan for semiconductors," October 2020, *https://www.semiconductors.org/wp-content/uploads/2020/10/Decadal-Plan_Interim-Report.pdf* (accessed on Oct. 24, 2021)

Figure 3.5: Cost-Efficient Environments Requiring Solutions

Each of these environments has its unique challenges, so a one-size-fits-all solution will not be able to provide efficiency across all scenarios. Compounded with the ever-increasing appetite for data and the essential nature of connectivity for economic development, it is critical that 6G provides innovative solutions in all aspects of the network architecture, including devices, wireless access, cell-site backhaul, and overall distribution. Increases in capacity must be offset with efficiency improvements, reducing the network's overall power consumption through more energy-efficient components and system architectures. Spectrum must become more available at all frequency ranges, including low-band, mid-band, mmWave, and even sub-THz. Complexity of wireless communication must meet the device type (e.g., wearables, self-powered devices, low-cost and low-complexity devices). Solutions must be based on open, interoperable architectures to improve efficiency and flexibly enable various services and deployments in a cost-efficient manner.

3.4.1 National Imperatives

IMT services have fostered economic growth and innovative new services that have become universal in the lives of North Americans. The demand for data services continues to grow unabated, while cellular devices are becoming more powerful, providing essential applications for industry and leisure. The recent pandemic has made remote working more common, furthering our reliance on connectivity for commerce. The sustained economic growth and welfare of North Americans relies on the improved efficiency of existing services in all environments.

Several areas would help foster cost efficient solutions:

- Business model (to facilitate 6G availability in rural areas).
- Infrastructure regulation (modify real estate requirements in order to improve the energy footprint).
- Spectrum (greater availability of spectrum, avoid fragmentation challenges and permit multi-band aggregation) issues at a national level.

3.4.2 Applications and Markets

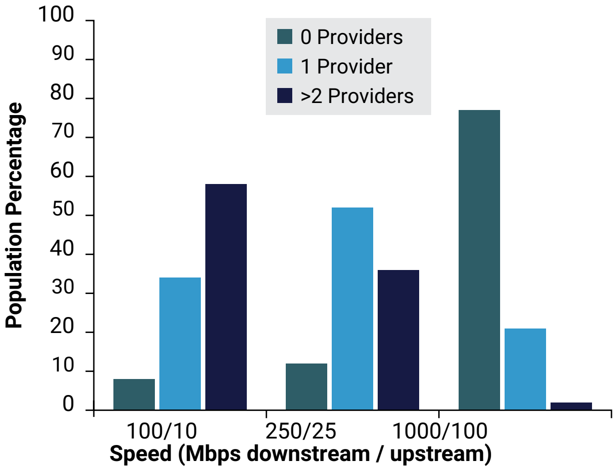
The markets for IMT services can be generally categorized as urban, rural, and indoor as listed in Table 3. The need for urban coverage is self-evident, being the focus of investment since the inception of IMT. Continued investment in the urban market segment is required to address the sustained demand and traffic growth.

Market Segment	Industry Challenges
Urban	» Capacity » Coverage
Rural	» Lack of supply-side competition » Low subscriber-density economics » Distribution cost structures
Indoor	» Penetration losses from out-door-to-indoor coverage » Physical and organizational partitioning in shared spaces

Table 3: Market Segment Considerations for Cost-Efficiency Solutions

The current situation for rural coverage in North America requires cost-efficient solutions for broadband coverage, reflecting the region's broad demographics and disparate geography. Based on the FCC broadband map,[3] illustrated in Figure 3.6, only 24% of the population is covered by 1 Gbps fixed broadband. Although over 80% have access to 250 Mbps service, 51% of them are covered by only one operator. Next-generation networks must improve the efficiency of delivering rural broadband coverage, making it more economical for multiple operators to compete and, through competition, provide more innovative services.

3 *https://broadbandmap.fcc.gov*, December 2020



Less than 24% US population covered by 1Gbps fixed broadband; only one operator providing 250 Mbps DL for 51% of population *(Source: FCC Broadband Map)*

Figure 3.6: Broadband Coverage in United States (December 2020)

Providing rural broadband continues to have some significant challenges. Unlike urban environments, population densities are sparse, increasing the cost per bit and making it desirable to support the largest possible cells. Remote or rural environments may have a higher need for broadband support spanning extensive distances, with speeds ranging from sensor/IoT connectivity to eMBB. However, physical constraints on the range of cellular links continues to be an impediment, especially at the higher frequencies. Similarly, distribution costs for backhaul and transport make it uneconomical to deploy rural networks, especially when the expected number of subscribers per cell is low. These challenges are reflected in both "normal" customer service and in the availability of emergency communications.

As we move toward 6G, ICT industries build on our experience from 5G. It is clear that providing coverage to indoor spaces remains a challenge given the penetration losses for outdoor-to-indoor coverage especially at higher frequencies (e.g., mmWave). There are challenges, as illustrated in Figure 3.7, to provide coverage to public indoor open spaces, offices with multiple partitions, factory spaces having many different shadowing obstacles, and malls (which can be a mix of both open and enclosed spaces). Residential indoor spaces are also challenging, but to some extent they have been addressed by fixed wireless access, which 6G must continue to support.

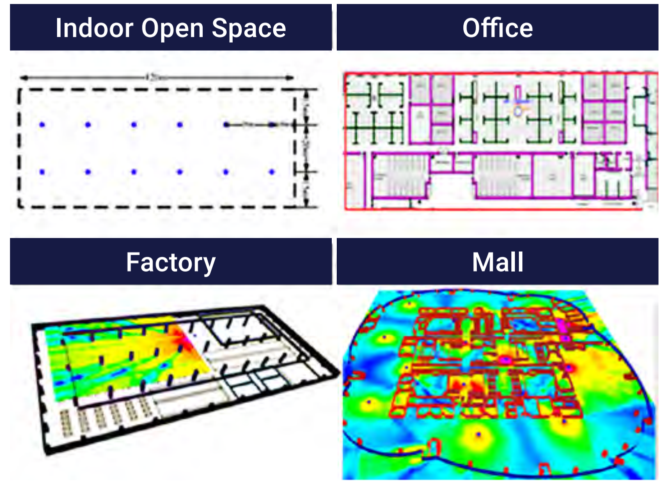


Figure 3.7: Challenges of Public Indoor Spaces

3.4.3 Technology Development

Several approaches are available to improve urban capacity and coverage, including cell densification, spectral efficiency improvements, and access to new spectrum. It is well known that cell splitting and small cells can improve area capacity. However, the economics of deploying smaller cells can be quite challenging given the cost of site acquisition and backhaul. Correspondingly, techniques to improve densification can also extend the utility of higher frequencies, such as mmWave by making deployment more economical on a large scale. One key component would be providing more efficient and lower latency wireless backhaul solutions. Innovation in network architectures and business models may also reduce costs associated with site acquisition and other CAPEX/OPEX.

Spectral efficiency improvements can also provide savings by lowering the cost per bit for an established network configuration. However, gaining new efficiencies over 5G may prove difficult as 5G is already very efficient. Some areas of interest include enhanced massive MIMO techniques looking at larger arrays with more elements, further leveraging narrower beams, and relying on greater spatial reuse. New modulation schemes that simultaneously improve energy efficiency and spectral efficiency may further reduce the complexity of devices in both user equipment and base stations. Access to new spectrum continues to be a reliable way of increasing capacity in urban environments. Sharing spectrum can open up access to coveted propagation-friendly lower spectrum. New spectrum at higher frequencies (e.g., sub-THz) can offer even higher peak rates. New innovative techniques for spectrum sharing among multiple operators can prevent fragmentation of spectrum, enabling higher peak rates while improving the typical user experience, particularly in lower spectrum. Finally, solutions that reduce the complexity of carrier aggregation between differing frequency ranges (both traditional low spectrum and new higher spectrum) can provide a greater total bandwidth to the subscriber.

Suitable regulations are needed to remove bottlenecks for innovative solutions that reduce energy footprint and real-estate requirements. Wideband PAs will continue to push innovation as multi-band radio products occupy less physical rack space than band-specific radios. Such designs require regulations allowing similar transmit output powers, common wideband filters across the served bands, and similar unwanted emissions limits. Ideally, spectrum availability should strive to facilitate cost-efficient devices by reducing spectrum fragmentation and the need for multi-band aggregation.

Innovations in network architectures and business models offer hope in improving the efficiencies of rural coverage. For example, integrating terrestrial and non-terrestrial networks could cover wider areas at a lower cost. Integration of satellites, drones, and high-altitude platforms may be used to provide both access for rural subscribers and backhaul for rural cell sites. The combination of terrestrial and non-terrestrial links can trade off range and capacity, improving the overall efficiency. Sharing spectrum and equipment may also provide cost savings in rural areas. Spectrum could be shared amongst multiple operators. Similarly, equipment and cell sites may be shared, reducing deployment costs. 6G networks should be flexible to accommodate different methods of sharing through open interfaces and the support of spectrum sharing techniques. Network cloudification will lead to cost savings in deployment, operation, capacity scaling, while enabling the roll out of new features.

The solutions for indoor public spaces are challenging, and significant research is needed to find effective solutions. One potential solution may be tighter integration of building-owned networks with cellular service provider networks, thus allowing a more seamless service experience for subscribers. 6G could further optimize dense small cell, remote radio head (RRH), and smart repeater deployments to provide higher capacity and better coverage indoors. Intelligent surfaces should also be studied as a green alternative to the active, RF-based solutions above. Spectrum for indoor public spaces should consider both licensed and unlicensed spectrum to distribute high-throughput solutions.

Technology Challenges	Description	Technology Considerations
Capacity	Growing traffic demand will impact the urban and suburban areas, depleting capacity. The cost per bit must be continuously improved by increasing spectral efficiency per unit area. Cell splitting and technology improvements can all contribute to the efficiency improvements.	Cell densification (see coverage) Radio technologies: » Advanced massive MIMO » New waveform, coding, modulation, multiple access schemes » AI in the air interface » Ultra-low-resolution data converters Spectrum efficiency: » Spectrum sharing: licensed, unlicensed, local, coexistence, with 5G during transition, and with dissimilar and possibly uncooperative systems, etc. » Carrier aggregation, ultra-wideband carrier » Higher frequency spectrum
Coverage	The utility of frequency spectrum needs to be improved through techniques that increase the coverage reliability to new environments at larger scales, and easing of real estate barriers.	Cell densification: » Low-latency/-cost backhaul » Open and virtualized RAN » Integrated access backhaul (IAB) » Smart repeater » Reconfigurable intelligent surface (RIS) » Improved, AI-based planning and self-optimization

Technology Challenges	Description	Technology Considerations
Lack of supply-side competition	Reduce the costs of deployments and increase the competition through innovative network architectures and standard interfaces.	Business-model innovation Network architecture: » Tighter integration of building-owned networks » Non-terrestrial networks, including collaboration between terrestrial and non-terrestrial networks » Distributed cloud platform » Network disaggregation » RAN-core split » Mesh network and sidelink » Cooperative communications » Lean protocol stack » Embedded sub-network connectivity
Low-subscriber-density economics	Develop deployment architectures that can maximize coverage in sparsely populated rural areas connecting the unconnected.	Business-model innovation
Distribution cost structures	Bringing capacity to large geographic areas will require cost-efficient long range backhaul to support the cells in sparsely populated areas. Rural communities should leverage turnkey solutions allowing deployments with little customized cell planning.	» Engineered reference designs facilitating ease of deployment for a set of typical rural deployment scenarios. » Information "interstate" providing local distribution points for rural communities and major transportation arteries.
Penetration losses from outdoor-to-indoor coverage	Capacity must be bridged from outdoor spaces to indoor spaces. Once indoors, effective distribution must be available to reach the indoor structures where people live and work.	Collaborative use of licensed and unlicensed spectrum
Physical and organizational partitioning in shared spaces	Distribution systems for indoor spaces providing commercial-grade service deployed by venue owner, industrial partner, or management company in a collaborative partnership.	Tighter integration of building-owned networks (interoperability, business-model)

Table 4: Technology Considerations for the Success of 6G Cost-Efficient Solutions

Goal #4: Distributed Cloud and Communications Systems

6G will provide Distributed Cloud and Communication Systems where communications/connectivity services work together with unified computing that scales across devices, network computing resources, and data centers.

3.5 Distributed Cloud and Communications Systems

One of the major drivers in network evolution is to merge mobile and cloud systems (e.g., the confluence of communications and compute in a distributed system). Future systems will be built on cloud and virtualization technologies. This enables separation of hardware and software and increased flexibility, performance, service capabilities, resiliency, and productivity. 6G systems will feature cloud-native capabilities that rely on cloud technologies. Cloud native refers to a system that has cloud designed for or built into it from the beginning. It describes the patterns of organizations, architectures, and technologies that consistently, reliably, and at scale fully take advantage of the possibilities of the cloud (to support cloud-oriented business models).

The growing amount of user devices typically has significant energy consumption constraints and increasing compute loads.[4] A 6G network compute fabric enables the seamless combination of compute and data resources and services from or in the device, edge, and/or cloud deep to optimize the performance and energy efficiency across 6G applications. Data can be processed beyond distant cloud (e.g., data centers) to intermediate cloud (e.g., concentrators, aggregators), edge cloud (e.g., eNB, relay) up to the device edge (e.g., UE, CPE). This provides a consistent data infrastructure for seamless access to data stored in multiple locations, as if from a single local access.

3.5.1 National Imperatives

The North American ecosystem has several major cloud and software providers and the most technologically advanced operators, making it uniquely well-positioned to lead and shape the transformation to cloud native mobile networks, with 6G being an integral part. Such cloud-native networks will drive off a network compute fabric that includes a multitude of area networks and X-as-a-service platform solutions. Within such a fabric, new systems and solutions can be built to deliver experiences for end users far beyond today's capabilities.

The confluence of communications, compute, distributed cloud, and virtualization technologies is a major driver in network evolution—and one where North America can leverage its expertise and ecosystem strengths.

Hence, one national imperative is to scale up North America's cloud ecosystem and support the merger of communications and cloud systems, as well as devices. This will promote the fundamental conditions for collaboration and funding of inter-disciplinary research (and innovation). Such a collaboration should ideally shorten the period between research, proof of concept, adoption, and launch of successive research efforts.

3.5.2 Applications and Markets

The convergence of mobile and cloud systems is strongly connected to the evolution of future mobile networks and the development of network compute fabrics to support low-latency mission-critical applications, among others. A cloud-native solution will lead to the development of network compute fabrics forming a substantial opportunity to cloud, software, and networking markets, in which North America has already the global leadership, as well as to emerging applications markets (e.g., industrial and IoT applications).

Applications (e.g., factory automation, collaborative robots, cloud and edge gaming, scalable digital twin) running at different levels of the network computing fabric can take advantage of the available data. They also can be custom-designed to take advantage of one or more of the unique attributes such as bandwidth scalability, low-latency offload, privacy-preserving denaturing, and WAN-failure resiliency.

The need to deal with physical/geographic distance and guarantee SLAs (e.g., low latency, coverage, energy efficiency), as well as imperatives about technological equity, privacy, and security, are some of the sources of the underlying demand for the 6G network compute fabric. The desire to deliver consistent network QoS and provide immersive experiences for anyone, anywhere, at any time, can be met by such network compute fabrics.

3.5.3 Technology Development

5G is the first mobile network generation focusing on communications, (edge) compute, storage, sensing, and actuation. Advances in 5G include virtualization of the network. 6G is anticipated to bring the full merge of mobile and cloud systems such that network compute fabrics at large scales can be deployed and lead to ubiquitous communications networks. With the increasing demand for low latency, coverage, and availability, this fabric needs to be extended to support the device-to-edge-to-cloud continuum. The introduction of the Device Edge, however, adds challenges in terms of discovery, scalability, mobility, and security. Device Edge opens the possibility of various stakeholders joining the ecosystem. Innovative services can be provided by third parties such as cloud service providers and application developers. To encourage the participation and to grow the ecosystem, a standardized way of device management, orchestration, service discovery, and traffic routing will be required.

Increasing demand for low latency, coverage, and availability present new integration and standardization opportunities along the device-to-edge-to-cloud continuum.

Future networks will have autonomic decision making capabilities that will depend on processing vast amount of data, available at different levels of the network. The available data will be best processed at the network level where it is available, limiting the need to move data. In some cases, if compute resources are not available, then data needs to be moved for processing. This can increase latency in decision making and increase privacy and security risks while reducing reliability as the process depends on network availability.

4 ITU-T L.1470, Greenhouse gas emissions trajectories for the information and communication technology sector compatible with the UNFCCC Paris Agreement, January 2020. *https://www.gsma.com/r/wp-content/uploads/2020/09/GSMA-State-of-Mobile-Internet-Connectivity-Report-2020.pdf*

Additionally, zero trust cloud-native architectures will be important in 6G by providing a strong root of trust while also establishing secure communications between entities (both cloud and physical network elements). As with any cloud-native workload, orchestration security tools that monitor and track security of the various cloud-native orchestration must provide a wide range of granular policy controls and compliance checks.

Technology Challenges	Description	Technology Considerations
Deployment of large-scale network compute fabrics	Enable full merge of distributed and interconnected mobile and cloud systems, at scale, and for ubiquitous access	» Federation and coordination » Homogeneous compute environment » Autonomous and autonomic networking » ML for network compute fabric optimization » Seamless compute distribution and offloading
Innovation, integration, and/or interoperability of edge devices	Unify computing scaling across devices, and in network computing resources and data centers	Support the device-to-edge-to-cloud continuum
Use of autonomic decision making techniques	Application of vast amounts of data at various levels of networks to improve the speed of decision making, privacy and security, and reliability	Distributed learning, federated learning, and split AI/ML
Provision of a root-of-trust	Enable support for zero-trust, cloud-native architectures	» Data trust fabric » Secure and signed telemetry » Distributed ledgers and block chains
Enable secure communication between entities	Enable support for zero-trust for cloud native architectures and communications between cloud and physical network elements	» Application- and session-based endpoint security » Network slicing for service and customer isolation
Provision of policy controls with corresponding monitoring capabilities	Capabilities required to support orchestration functions and to monitor compliance and security performance	» Closed control loops with integrated AI/ML, analytics » Adaptive policies and context-ware policies » Harmonized telemetry of network and platform resources

Table 5: Technology Considerations for Distributed Cloud and Communications Systems

Goal #5: AI-Native Wireless Networks

An AI-Native future network is needed to increase the robustness, performance, and efficiencies against more diverse traffic types, ultra-dense deployment topologies, and more challenging spectrum situations.

3.6 AI-Native Wireless Networks

AI and ML tools have substantially enhanced the fields of computer vision, image processing, natural language processing, robot navigation, etc., with a wide-ranging impact on our lives. The field of wireless communications won't be an exception. The Next G Alliance envisions the future 6G wireless system as being designed in an AI-Native way. This means AI is incorporated into major functionality from the very beginning of the system's design and development cycle. An AI-Native 6G system will leverage AI techniques (e.g., ML, deep learning, neural networks) for the design, deployment, management, and operation of various network and device functions. This will result in increased robustness, performance, and efficiencies to bring enormous economic impact.

3.6.1 National Imperatives

North American leadership in AI is of paramount importance to maintaining economic and national security and to shaping the global evolution of AI in a manner consistent with our nations' values, policies, and priorities. For example, the U.S. government has recognized that the advancement of AI research and deployment of a country is becoming a driver of the country's core competitiveness. Both the Trump and Biden administrations have paid special attention to the development of AI; the advancement of AI and 6G are universally agreed upon as widely championed bi-partisan priorities. This thrust brings them together to focus on how AI can fundamentally enable breakthrough 6G performance and technology to lead both priorities.

The Next G Alliance's goal is to promote critical applications of AI in the next generation of wireless to advance the North American leadership in the field of wireless communications and fulfill market needs. To reach this audacious goal, effort is needed in three important aspects:

- The 6G wireless standards need to be developed in an AI-Native way, with an open architecture to allow applications of rich set of AI algorithms.
- Open datasets need to be made available to the research and development community to expedite the AI application.
- Operators need to embrace AI as their new tool for increasing efficiency and quality of service.

> 6G wireless systems will incorporate AI natively from the very beginning of the system design and development cycle, substantially increasing system robustness, performance, and efficiencies.

We envision the application of AI will take steps, from optimizing individual function or module, to joint optimization of multiple functions or modules, and eventually achieving the goal of end-to-end application of AI. We expect the initial application of AI by 2025, with advanced applications by 2030 (Step 2). There is also a chance that we can see the initial effort of end-to-end AI applications, but it is more likely this will happen beyond 6G.

The successful application of AI/ML to 6G will have enormous economic impact on the telecommunication industry driven by automation of network operations, a shift in how networks are designed and implemented, a need for new hardware platforms, and higher efficiency of network performance across multiple dimensions such as energy efficiency, computational efficiency, and spectral efficiency. This in turn will lead to large impact on society both from consumption and workforce points of view.

3.6.2 Applications and Markets

AI/ML can be applied to solve different types of real-world problems in the field of wireless communications. First, it can be used to solve problems where only sub-optimal solutions can be implemented because of the optimal solution's complexity. For these type of problems, AI/ML offers the potential to improve performance at lower or comparable complexity for such problems. Second, there are problems for which analytical models are available but optimal algorithms are unknown. AI/ML has the potential to improve the performance for such optimizations. The third category of applications are ones where it is difficult to even analytically model the problem or scenario involved. In this case, AI/ML has the potential to tackle the problems in a completely new way.

From the perspective of OSI layering, AI/ML can be applied to all layers of communication systems. At the PHY layer, end-to-end optimization—from channel coding through digital pre-distortion and receiver processing—has been out of reach. End-to-end learning can be implemented through autoencoder-based deep learning approaches or similar. At the MAC layer and radio resource management (RRM) level, AI/ML can be applied to learn new signaling protocols with high efficiency that are adapted to the specific traffic models. Moving up to the network operation and management layer, we expect numerous applications, such as load balancing, energy-saving optimizations, interference management and mitigation, spectrum sharing and coordination in heterogeneous bands, handover optimizations, and antenna tuning. Lastly, while AI/ML introduces concerns for trust (see Goal #1), AI/ML also shows great potential in enabling security and privacy. For example, AI can provide security services such as user authentication, access control, anomaly detection, and attack detection.

3.6.3 Technology Development

All system elements—including UEs, base stations, and network core—are expected to run some form of AI/ML processing. They will face related challenges, such as energy efficiency and processing in the device, scaling, and capacity in the network. The following table attempts to summarize some of the technical challenges for the adoption of AI/ML technology in 6G systems.

Technology Challenges	Description	Technology Considerations
Compatibility and Interoperability	When the end-to-end link is adapted dynamically through learning, a key challenge is to enable harnessing of the spectral efficiency gains while ensuring broad and global interoperability.	» Diverse data collection » Distributed and supervised end-to-end learning » Transfer and federated learning » Native AI interface » Co-operative inference and learning » AI-based privacy and security
Minimum Performance Guarantee	By their nature, AI/ML algorithms cannot be rigidly defined in the same manner as conventional algorithms. This creates the need to have a much more comprehensive performance evaluation. Resilience in adverse conditions should be a key consideration. Fail-safe backup mechanisms maybe needed.	» Performance monitoring of deployed AI/ML algorithms » Fail-safe backup mechanisms » Dynamic model adaptation
Datasets and AI/ML Validation	Due to the crucial role of data in AI/ML, the creation of datasets, the depth and breadth of coverage of such data, and the methods for interoperability, validation, and test cases for AI-driven methods need to be carefully considered in the context of data and simulators.	» Diverse data collection » Proof of concept » Extensive validation frameworks
Computational Complexity	ML inference engines can have very high computational requirements, but these should be assessed against the projected rapid increase in capacities of ML hardware accelerators and, by comparison, to the complexity of existing methods.	» Specialized hardware accelerators » Distributed and supervised end-to-end learning » Assessment of computational complexity » Latency reduction
Overhead Management	There is a potential of increased overhead (e.g., sensor data) in some aspects of an AI-enabled system, and a potential for decreased overhead (e.g., reference channel in OTA). There is a trade-off among factors such as stimulus-response latency, overhead, and performance gains, which has to be studied.	» Native AI air interface » Distributed and supervised end-to-end learning » Data-driven modeling » Transfer and federated learning
Provision of Policy Controls with Corresponding Monitoring Capabilities	Capabilities required to support orchestration functions and to monitor compliance and security performance.	» Closed control loops with integrated AI/ML, analytics » Adaptive policies and context-ware policies » Harmonized telemetry of network and platform resources

Table 6: Technology Considerations for AI-Native Wireless Networks

Goal #6: Sustainability

The 6G system will be sustainable and respectful of the environment, not only by providing more energy-efficient networks and devices, but also by implementing circular economy principles and by reducing its environmental impact on material, water, land, and air.

3.7 Sustainability

Scientific reports have raised global awareness around climate change in the past five years and convinced the U.S., Canada, and most other worldwide governments to commit to keeping global temperature increases to well below 2°C above pre-industrial levels.

Climate change and carbon footprint concerns make it vital to reflect energy efficiency and sustainability considerations, both in 6G networks and the applications that use them.

The challenges of global climate change and the need to reduce our carbon footprint makes it vital that 6G networks reflect the most energy-efficient available technologies, reducing our dependence on non-renewable sources and using renewable and ambient sources of energy.

Energy consumption is not the only aspect to consider for achieving these goals and conserving our planet. Beyond energy consumption and emissions, the ICT sector's overall environmental impact also must be considered, including water consumption, raw material sourcing, and waste handling.

The energy-efficient approaches used by 6G networks will serve as a model for energy efficiency and environmental stewardship for applications that will employ these networks, enabling other vertical industries to achieve their own targets to reduce greenhouse gas (GHG) emissions.

Overall, the roadmap effort will examine ways in which 6G can contribute to our "green" future, propose technological initiatives to gain that future, and help us realize the green, energy-efficient information technology ecosystem that will benefit our world:

- » Increased energy efficiency across infrastructure devices, and applications that attain the sustainability goals despite growing 6G traffic volumes.
- » Reduced non-recyclable materials in devices and programs to better reuse/reclaim material from unserviceable devices.
- » Reduced CO2 footprint of network infrastructure hardware and software within hosted facilities (e.g., equipment racks, data center) per services rendered.
- » Efficient use of natural resources and reduction in waste and pollution in industrial processes through improved technologies, monitoring, and intelligent control.

3.7.1 National Imperative

The ICT sector's sustainability is related to the use of energy and its environmental impact. Reducing energy consumption and decarbonizing the energy supply are the most important tasks that the sector can undertake to reduce its emissions. It is important to account for the ICT sector's overall environmental impact, scope 1-2-3[1] GHG emissions, as well as water consumption, raw material sourcing, and waste handling. This can be achieved by transition to a circular economy: an economic system that comprehensively tackles global challenges such as climate change, biodiversity loss, waste, and pollution.

These sustainability objectives represent the current and long-term imperative that will require the public and private sectors to cooperate to advance North American interests in achieving these goals as the development of 6G technologies commence over the next few years. North America has significant expertise and leadership across four key areas that will be critical to driving the 6G strategic objective for a green future:

- » Design and manufacturing of materials and electronic components, such as silicon, integrated circuits, and battery technologies, that will be more energy efficient or use ambient/zero energy, are recyclable and do not produce toxic waste.
- » Advanced data modeling, AI, and process automation that will reduce energy consumption by dynamically predicting, managing, and optimizing 6G infrastructure deployments for coverage, capacity, and energy efficiency.
- » Design of radio technologies that optimize spectrum use while ensuring that 6G devices communicate with utmost power efficiency.
- » Data center facilities that are designed to be carbon neutral.

North America expects to make important contributions in component design and manufacturing, advanced data modeling and optimization, power-efficient radio technologies, and carbon-neutral data center facilities.

North America is well-positioned through these key areas to drive 6G innovation in energy and environmental conservation technologies globally.

3.7.2 Applications and Markets

Climate challenges are expected to seriously disrupt business as usual and change the way citizens worldwide live their lives.

As more companies commit to adopting corporate and social responsibility (CSR) strategies that address environmental and social issues, many companies have a sustainability program in place that commits to reducing their energy consumption and environmental impact. For communications service providers, 6G infrastructure will be green by design, making their sustainability goals realistic and achievable even as the traffic volume they handle continues to grow.

6G communication services could provide supply chain green identity credentials and energy consumption metrics enabling the service provider to manage its supply chain of virtualized services, knowing it meets agreed KPIs and supports their sustainability goals.

Enterprise customers operating over 6G infrastructure can use these energy efficiencies and green credentials to reduce their own environmental impact in support of CSR sustainability goals. No singe organization alone will achieve a significant impact on climate change. However, by enabling millions of businesses globally to reduce their energy and environmental impact, 6G collectively will have a profound effect on climate change.

Equally, consumer awareness and trends toward more conscious consumption have accelerated over the past decade. Consumers worldwide now expect companies to behave in more sustainable and eco-friendly ways. As with consumers who purchase coffee only from ethical supply chains or source energy only from providers using high percentages of renewable sources, this trend is extending to communications service providers that already share the energy consumption associated with their mobile services in some countries or sell recycled devices, for instance. 6G device manufacturers, service providers, and related businesses will be able to use the green credentials to be competitive and differentiate themselves in the market.

3.7.3 Technology Development

Here are some examples of how 6G can achieve these objectives:

Technology Challenges	Description	Technology Considerations
Energy Reduction	Radio technologies and components designed for energy efficiency including data converters, systems-on-chip (SOCs), and power amplifiers.	New waveform, coding, modulation, and multiple access schemes, pre-distortion, ultra-low resolution data converters, SOCs with higher levels of integration, and higher-dimensional massive MIMO.
	Energy-efficient infrastructure with optimized compute, network, storage, and data center facilities.	Dynamic optimization of infrastructure components to meet the demands of the 6G network but without idle resources.
	Use of AI/ML to optimize network dynamically, thereby reducing the energy consumption of base stations, devices, and core network.	Dynamic optimization of 6G network to ensure optimal availability of service, without idle resources.
	Adaptation of connectivity protocols to allow idle connections and dramatically reduce device and radio power consumption, saving battery and RF power.	RF protocols and spectrum power optimization.
	Device energy harvesting with a true ultra-low-power interface to alleviate battery drain or minimize the need for battery replacement over its lifetime.	Regenerative/zero-energy devices.
	End-to-end observability to establish KPIs that can form a composite measure of component energy consumption and efficiency.	Data pipeline for enhanced observability of RAN, cloud, core, and service metrics.

Technology Challenges	Description	Technology Considerations
Environmental Impact Reduction	Improve water consumption such as liquid cooling or monitor water consumption. Metrics like the water usage effectiveness introduced by Green Grid can be used to track progress in water savings.	Classification of "ECO rating" based on the lifecycle assessment of products and services for KPI reporting.
	Reduce direct and indirect impacts on land. Improve the process of mining for rare materials needed to manufacture electronics. Track and reduce the environmental impact of material and rare material extraction. Evolve to bioplastics and more sustainable material. Increase recyclability, reduce waste, and minimize waste environmental impact.	
	Consumers should be more environmentally responsible, protect their health and reduce energy consumption. Provide tools for consumers to monitor and act on their consumption to reduce their environment impact.	Network slice including application usage meets specific green credentials, providing consumer choice over communications channels that are green.
Technology Enablement	Use of green credentials and metrics of the supporting communications infrastructure to measure and select most efficient resources.	Real-time supply chain management and KPI reporting.

Table 7: Technology Considerations for Sustainability

4 North American 6G Roadmap Lifecycle and Timeline

4.1 Lifecycle Roadmap

The 6G lifecycle is composed of research initiatives, development and manufacturing, standards leadership, market readiness, commercialization, and the eventual evolution of the 6G system with new features and functions. Figure 4.1 illustrates these components of the lifecycle, which are valid for initial 6G systems and subsequent ones.

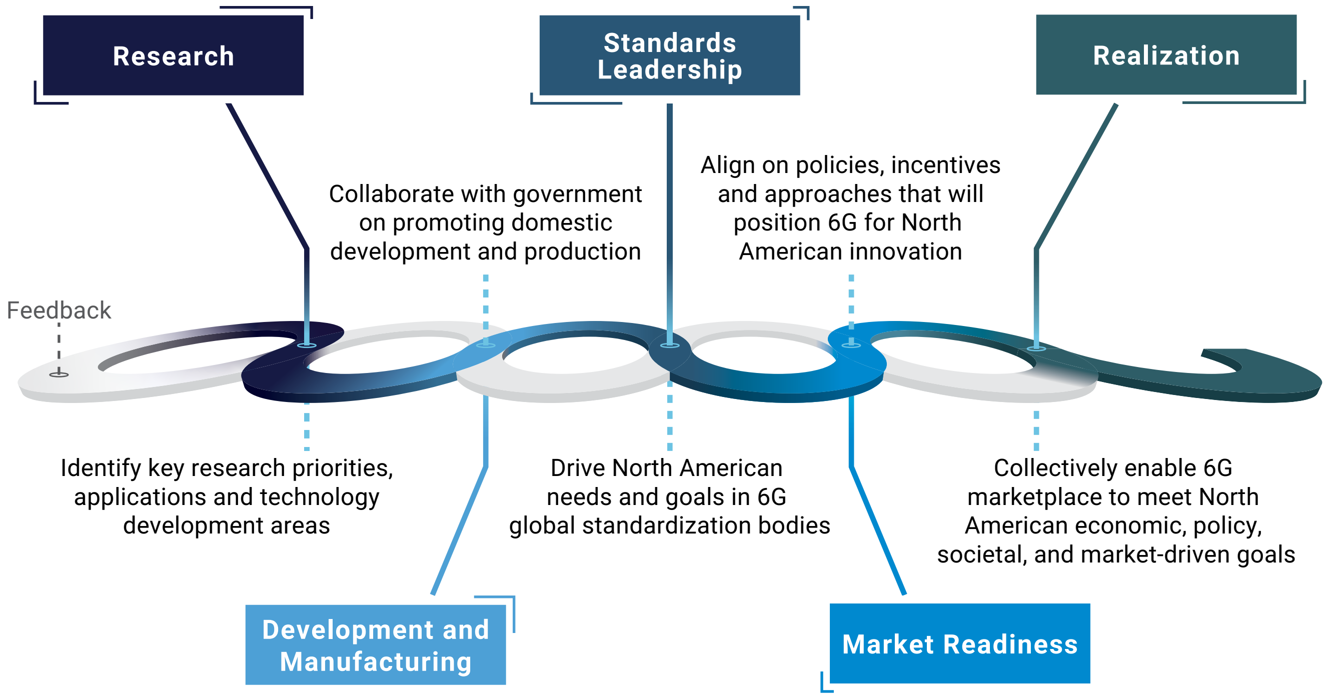


Figure 4.1: Next G Alliance Lifecycle Roadmap

Basic and applied technical research—which aim to develop a better understanding of the laws of the nature and apply them to solve technical problems respectively—are in general independent of the lifecycle of mobile systems. Research creates opportunities and sets limitations and capabilities of the technology available, as input into the experimental development phase. To advance North American leadership, it is important to connect applied research opportunities and priorities to the goals of 6G commercialization. Early research can lead to outcomes across all elements of the Next G lifecycle, such as future job skills.

Within the development and manufacturing cycle, 6G experimental development represents systematic work that leverages knowledge gained from research and practical experience, while producing additional knowledge directed at new 6G products. This step includes concept development, prototyping and technology demonstration, setting the stage for the development of 6G products, and related processes.

The product and process development cycle is concerned with subsystem or system-wide implementation, testing, and trials, leading to the eventual production and market introduction of 6G devices and infrastructure equipment for wide deployment and commercial operation of 6G systems. Early collaboration between industry and government actions in this phase can incentivize the private sector in areas like domestic manufacturing, R&D tax credits, and start-up incentives, facilitating a more secure and reliable 6G supply chain.

6G technical standardization, development, and commercialization, will benefit from prior scientific advances achieved during the basic and applied research phases and the related basic technology component trials from the experimental development. Standardization is used to develop the best technologies for 6G, based on the available research results. Standardization is based on cooperation among interested parties working towards the development of technical specifications based on consensus. Standardization complements market-based competition, typically in order to achieve objectives such as the interoperability of complementary products/services, agreed upon test methods, functional requirements, and non-functional requirements (e.g., safety, health, environmental performance, etc.).

In order to achieve global interoperability, mobile systems are specified and standardized in international forums, such as ITU and 3GPP. The ITU approach is for external organizations and members to submit their 6G technical proposals for consideration. It is expected that the main technical specification of 6G systems will be done in 3GPP in order maximize global harmonization. It is critical that North America takes a leadership role in the development of 6G specifications and standards. While standards should continue to be private-sector led, alignment between industry and government on key drivers for North American success will ultimately deliver standards that meet North America's marketplace needs and values.

The development of 6G systems is expected to happen in parallel to various stages of the standardization effort; testbeds and trials can be used to validate technical choices made during standardization and to obtain experience with implementation options. Additionally, during the deployment and commercial operation, new services requirements will emerge for an evolution of the 6G systems, with input into the research, innovation, and development lifecycle.

Progression in 6G development and standardization should lead to a proactive market readiness stage, where policies and incentivized innovation can set the stage for a robust 6G marketplace. Market-ready spectrum policies and incentives for widespread 6G deployment would lay the groundwork for rapid commercialization and deployment. It is imperative for industry and government to cooperate on policies and actions that facilitate strong market readiness for 6G.

The Next G Alliance's ultimate goal is realization of 6G into a robust North American and global marketplace by end of this decade. Collaboration between the private and public sector in North America throughout the research to realization lifecycle can help achieve key societal goals like enabling the workforce of the future and closing the digital divide.

Effective public-private collaboration, across the research to realization lifecycle, will determine market success and the attainment of societal goals.

Central to the Next G Alliance's mission is the alignment on a collaborative roadmap that brings the power of North American leadership to apply the lifecycle approach to the delivery of robust 6G systems. By the end of this decade, North American leadership in 6G will produce:

- A more powerful work collaboration across industry, government, and academia that is aligned across the full the research-to-commercialization lifecycle.
- A robust marketplace using innovative applications and technologies that connects society in a new digital world.
- Increased ownership of technology advancements that are deployed and enable the 6G vision.

4.2 6G Timeline

The 6G timeline is under development by SDOs, 3GPP, ITU, and other interested organizations. ITU-R Working Party 5D (IMT Systems) is responsible for overall planning for IMT (International Mobile Telecommunications) systems and develops its schedule based on input from SDOs, specification groups, and industry.

The Next G Alliance is aligned to the general industry consensus of a 2030 target date for completion of the ITU-R's "IMT Vision for 2030 and Beyond."

The Next G Alliance provided its view of the proposed ITU "IMT Towards 2030 and Beyond" (6G) timeline to ITU-R Working Part 5D (IMT Systems) in October 2021.[5] The ITU continues to discuss the overall timeline and is scheduled to conclude the "IMT Vision for 2030 and Beyond" Recommendation in July of 2023. The Next G Alliance is aligned to the general industry consensus of a 2030 target date for completion of the ITU-R Recommendation.

Figure 4.2 describes the overall process towards the recommendation, which is consistent with the process that occurred for IMT-2000, IMT-Advanced, and IMT-2020. The green boxes in the figure indicate work already in progress; blue boxes indicate work that is planned to occur. The "Technology Trends Report" lays the groundwork for the overall technology enablers/concepts and is scheduled to conclude in mid-2022. The IMT "Feasibility Above 100 GHz Report" is scheduled to conclude in mid-2023. The IMT Vision Recommendation, scheduled to conclude in mid-2023, provides overall guidance regarding the final "ITU-R Recommendation on IMT-2030 and Beyond."

The ITU-R WP 5D schedule proposes that development of the technical performance requirements begin in 2024 (TBC). These requirements are used for the evaluation criteria and methodology for organizations wishing to submit their technology to ITU-R WP 5D. The submission templates provide uniformity for the evaluation process.

An "IMT Towards 2030 and Beyond" workshop is proposed in the 2026 timeframe (TBC) which basically initiates the process for the technology submissions.

The submission process for technology proposals is scheduled to begin in 2027. This process consists of a time period allowed for the submissions, an evaluation period,

5 *[795] Reply liaison statement to External Organizations, development of "IMT Vision for 2030 and beyond" (itu.int)*

a consensus building period, and a decision. During the consensus-building period, proposals may be combined/merged/harmonized to simplify and clarify the ultimate Recommendation. The Recommendation would then be approved in the 2030 timeframe (TBC).

SDOs and other external organizations contribute to the process. The most prominent contributor to date has been 3GPP. The 6G timeline has not yet been formally discussed within 3GPP; therefore, no 3GPP timeline for 6G is included in this report. As noted above, the ITU derives its schedule from various input sources. Should the schedules of 3GPP or other organizations change, those changes would need to be communicated to ITU so they can consider any potential adjustments to their timeline.

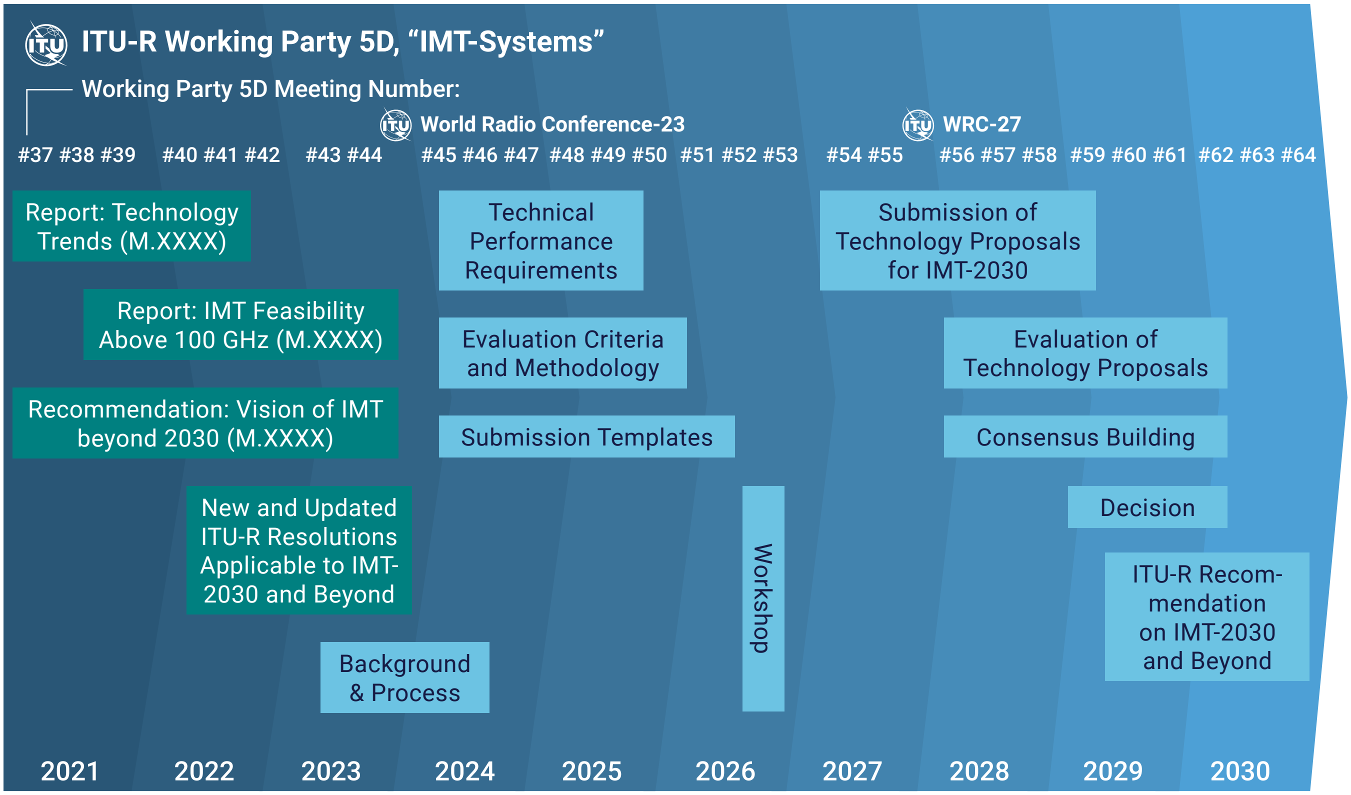


Figure 4.2: Next G Alliance Proposed Timeline for "IMT Towards 2030 and Beyond"

5 Societal and Economic Needs

As we begin defining 6G and identify the required infrastructure capabilities, there is a unique opportunity to consider how to address critical North American societal and economic challenges such as climate change impact, digital equity, and sustainable economic growth. Additionally, there is an opportunity to advance the United States' historical commitment to leadership in upholding human and civil rights (including rights around digital access), as well as emerging leadership around climate change.

> Digital equity, trust, sustainability, economic growth, and quality of life are key pillars in addressing the interdependencies between human and technological evolution.

5.1 Key Priorities and Requirements

The approach taken to identify and prioritize relevant social and economic issues is informed by Environmental, Social and Governance (ESG) factors. The first step is to establish a base inventory of social and economic issues, which can then be grouped into common outcomes and connected to needs identified by the United Nation's Sustainable Development Goals (SDGs). These SDGs provide "a shared blueprint for peace and prosperity for people and the planet, now and into the future."[6] As the inventory of issues and thus outcomes are further defined, there will be opportunities to identify future areas for research, technology investment, and market opportunities. Five groups of common outcomes emerge from this process as described below.

5.1.1 Digital Equity

Digital equity should be understood as a requirement to achieve three conditions for each user:

- **Affordability:** Affordability is an enabler of Digital Equity and Accessibility, subject to policy and market forces. 6G user equipment and the 6G network architecture must be cost effective and with improved operational efficiency, thereby reducing overall cost of access to individuals.
- **Accessibility:** 6G technologies, providing multiple modal forms of access/communications, must be accessible to all members of the population.
- **Geographic availability:** 6G network services must be available to the entire population of potential users.

Digital equity means all individuals and communities have access to a reliable broadband connection, thereby playing an important role in achieving several U.N. SDGs. Internet access supports greater access to education, employment, and economic growth. The result is a society that is inclusive and allows participation from all components of society, increasing innovation and spurring sustainable industrialization.

5.1.2 Trust

The 6G system must offer a valid and safe entry point to information services, with demonstrable compliance with well-defined ethical frameworks, to ensure that users trust it to the greatest degree possible. Key components of trust include:

- **Security:** 6G security must ensure that information is delivered between endpoints without being illegally intercepted or tampered. The network, including associated computational and storage resources, must be secure against external attacks.
- **Data privacy:** The vast volume of personal or proprietary data being generated and tracked introduces increasing privacy and ethical use concerns about what kind of information is being passed and to whom. While privacy is a fundamental right of a person, network operators and application providers are responsible for ensuring that there are no unlawful uses of their network and personal data. Therefore, there is a need to balance privacy along with required regulatory requirements.
- **Resiliency:** The 6G system should be capable of detecting and mitigating anomalies or disturbances that compromise security and reliability. Networks should serve critical use cases with high reliability, must be highly resistant to disruptions, and must degrade gracefully in performance when compromised by faults, disturbances, attacks, and external disasters.

Trusted entry points that provide identifiable and attestable entry and egress to 6G services are an essential part of the resilient infrastructure identified in numerous UN SDGs.

5.1.3 Sustainability

The World Commission on Environment and Development (1987)[7] defined sustainability as the ability "to meet the needs of the present without compromising the ability of future generations to meet their own needs." Sustainability is the balancing of economic prosperity, environmental protection, resource conservation, social well-being, and equity.

6 *https://sdgs.un.org/goals*
7 *https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf*

Climate experts have identified reduction of CO2 emissions as the lynchpin for combating climate change. It is vital that 6G technologies continue to improve the carbon footprint of ICT technologies with energy-efficient operation and environmentally sustainable supply chains. A key approach to energy efficiency is greater reliance on renewable sources of energy. The sustainability and energy-efficient principles applied to 6G systems will in turn serve as models for energy efficiency and environmental stewardship. Furthermore, 6G will prioritize the increasing urgency for aggressive climate action by employing ICT to reduce human impact on the environment, thereby improving the safety and well-being of peoples around the world.

The social and economic aspects of sustainability are closely connected to a broader set of environmental concerns:

» Reduction of direct and indirect GHG emissions.

» Promotion of sustainable use of energy, water, land, and materials across the entire value chain for 6G telecommunication infrastructure and technologies, encompassing raw materials, supply chain, operation, and disposal.

5.1.4 Economic Growth

Economic growth might be fostered by leveraging 6G capabilities to increase productivity, innovation, efficiency, effectiveness, and to create new value propositions, business models, and market segments. In addition, economic and societal benefits in North America and its local communities are strengthened through advancements in:

» Manufacturing and supply chains—6G technologies should provide opportunities for North American manufacturing.

» Workforce development.

5.1.5 Quality of Life

6G-enabled services will be important to improving the quality of life in North America and its local communities. They apply to areas such as public services, health care, education, safety and security, and the environment. They also support human rights, freedom, peace, and democratic values. Existing and emerging societal needs include:

» **Health Care:** Offer better support for health care with advancements in intelligent health care, monitoring and controlling of infectious disease, telemedicine, remote surgery, connected ambulances, and automatic processing to increase the effectiveness of public health services to ensure healthy lives, improved health care, increased longevity, and quality of life.

» **Education:** Improve education by enabling digital representations of the real world alongside immersive communication.

» **Safety and Security:** Improve the safety, security, and well-being of North Americans and local communities and protect human rights and fundamental freedoms.

» **Environment:** Enhance the quality of life impacted by environmental causes.

5.1.6 Mapping of Issues to UN Sustainable Development Goals

The five groups of common outcomes that Next G Alliance recommends prioritizing for North America align with the UN SDGs as shown in Table 8. These alignments were identified based on where 6G can have more direct impact.

	United Nations Sustainable Development Goal	Digital Equity	Trust	Sustain-Ability	Economic Growth	Quality Of Life
1	End poverty in all its forms everywhere	•	•		•	•
2	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture		•	•	•	•
3	Ensure healthy lives and promote well-being for all at all ages		•	•	•	•
4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	•		•	•	•
5	Achieve gender equality and empower all women and girls	•	•		•	•
6	Ensure availability and sustainable management of water and sanitation for all			•		•
7	Ensure access to affordable, reliable, sustainable, and modern energy for all			•	•	•

	United Nations Sustainable Development Goal	Digital Equity	Trust	Sustain-Ability	Economic Growth	Quality Of Life
8	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all	•		•	•	
9	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation	•	•	•	•	•
10	Reduce inequality within and among countries	•	•	•	•	•
11	Make cities and human settlements inclusive, safe, resilient, and sustainable	•	•	•		•
12	Ensure sustainable consumption and production patterns			•	•	
13	Take urgent action to combat climate change and its impacts			•		•
14	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development			•		
15	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss			•		
16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable, and inclusive institutions at all levels	•	•			•
17	Strengthen the means of implementation and revitalize the global partnership for sustainable development	•				

Table 8: Mapping of Issues to United Nations Sustainable Development Goals

5.2 Overall Summary and Recommended Actions

There is a symbiotic relationship between technology and a population's societal and economic needs. As technology shapes human behavior and lifestyles, those needs shape technological evolution. Issues around digital equity, trust, sustainability, economic growth, and quality of life are both societal and economic imperatives. These are therefore outcomes for 6G systems to target, given the associations brought forth in Table 8. Achieving these outcomes will require an integration of these social and economic issues throughout the full 6G lifecycle of research and development, manufacturing, standardization, and market readiness.

6 Applications and Use Cases

The Next G Alliance is exploring new opportunities that are anticipated to arise from 6G applications. This will help organizations in North America plan for changes in market and technology dynamics. The use cases behind these applications and markets can be summarized into four foundational areas:

1. **Living:** How to improve the quality of everyday living.
2. **Experience:** How to improve the quality of experience in areas such as entertainment, learning, and health care.
3. **Critical:** How to improve the quality of critical roles in sectors such as health care, manufacturing, agriculture, transportation, and public safety.
4. **Societal:** How to attain and improve on high-level societal goals.

The mapping of use cases to the foundational areas is not exclusive. Some areas have a certain degree of commonality.

6.1 Key Priorities and Requirements

This section describes each of the four foundational areas and associated requirements, as depicted in Figure 6.1.

Figure 6.1: Foundational Areas for 6G Applications and Use Cases

6.1.1 Living – How to improve the quality of everyday living

With the enhanced capabilities, sensing and actuation deeply integrated in the 6G fabrics, humans are expected to be the ultimate beneficiaries of 6G. For example, Ambient Intelligence delivering seamless immersive experiences regardless of the point of consumption will open new doors for development of human centric technologies. This will not only improve our daily lives, but also positively influence human behaviors, in turn advancing the societies they create.

An important driver of change is the size of the workforce necessary to support everyday living due to the global trend of an aging population. According to U.N.'s "World Population Ageing" report,[8] old-age dependency ratios were highest in Europe and North America, with 30 persons aged 65 or older per 100 persons aged 20-64 years (the "working ages"). This ratio is projected to rise considerably, reaching 49 per 100 in Europe and North America in 2050. This trend will increase the need and market potential for intelligent assistance of humans. Example applications include caregiving, delivery assistance, and travel assistance,[9] which are considered new business opportunities.

8 *World Population Ageing 2019*, The United Nations. Available online at: *https://www.un.org/en/development/desa/population/publications/pdf/ageing/WorldPopulationAgeing2019-Highlights.pdf*

9 K. Lee, "A Smart Network of Service Robots," *IEEE Communications Magazine*, vol. 59, no. 8, August 2021.

The functional requirements and capabilities necessary to support humans' everyday living typically include enhanced human-machine interactions within the end device, such as service robots or other kinds of end user devices. They also allow human users to experience services as if they were speaking with human assistants, human caregivers, or human workers who help those human users. Enhancements to the interaction capabilities between communications layers and applications layers will enable 6G systems to serve the complex requests made from applications layers in a more timely and reliable manner. In addition, enhancements to sensing capabilities and the network fabric are important to support autonomous assistance (e.g., autonomous maneuvering of service robots, automatic security surveillance, automated decision making with explainable AI for human users) as ambient intelligence. High-level requirements associated with these usage scenarios include the following:

- Capability to recognize physical environments for autonomous maneuvering; surface sensing, object detection, estimation of trajectories (linear, circular, and/or ellipsoidal trajectories).
- Capability to share intents (e.g., maneuver) and to support negotiation among a group of participating service robots (competitive vs. collaborative).
- Reliable communication, a longer range of communication, out-of-coverage support with a suitable means of authentication, and authorization/change of authorized privileges, etc.
- Ability to support higher data rates (potential need of new spectrum band to use or new mode of spectrum usage).
- Very efficient support of exposure between the communication and applications layers.
- Secure mechanism(s) that can support 6G services and provide service resiliency for users.
- Capability to securely configure devices and networks with personalized preferences and settings of users in real time. This should allow users to experience personalized products and services (e.g., personalized hotel experiences, personalized shopping experiences).
- Capability to dynamically change experiences (e.g., content, device, or network settings) based on context of the user (e.g., user's identity, user's surrounding, user's emotional state).

6.1.2 Experience - How to Improve the Quality of Experience in Areas such as Entertainment, Learning and Health Care

One of the Next G Alliance's audacious goals is 6G DWEs. These use cases target services in the field of human-machine interactions, technology-mediated human-to-human interactions, physical and psychological health assistance, mixed-reality entertainment, and real-time interactive gaming with physical interactions. They appear in classroom settings, powered with mixed reality content and robotics, and in transportation systems using XR-enriched, Simultaneous Localization and Mapping (SLAM) capabilities, for example.

For these types of application, the efficiency and the quality of the display is crucial. In order to construct a direct feedback loop between human, digital, or physical entities and their counterparts, sensing capability with a reliable high bandwidth, low-jitter, and low-latency network connection is a must. Furthermore, enriched contents and personalized experience generated through edge or cloud intelligence (AI/ML) will make the applications and services more appealing. On top of all of these, security and privacy protection for human users cannot be compromised all through the services.

Although some "experience" use cases can be powered by 5G networks, there is a major expectation to refine or improve the feasibility and 6G user experience through a more advanced network, building on the following feature requirements:

- **High-Quality Media Interfacing:** Ultra-high-resolution displays (8K, 16K, or higher for medical imaging) or holographic projections will be crucial for user experience. The amount of network bandwidth required will depend on the quality of each picture frame and the frame refreshing rate. Audio or other physical signals (e.g., pressure, moisture, or heat) are likely to consume much less bandwidth than visual displays.
- **Different Classes of Delay and Latency:** The needs for minimum delay and latency will differ according to the type of applications. For example, in order to maintain the agility of maneuvering a racing drone, the end users will need much lower delay for control signals and least latency for sending video images. Under a different scenario, the minimum delay and latency for sending the instructions and high-quality pictures or video in an interactive classroom can be relaxed compared with drone racing. There may be other levels of the expectation in delay and latency for interactions with field robots in industrial or commercial-focused applications.

- **Personalized or Highly Customized Data:** The perceived value of the application will be greatly boosted when the application is personalized according to a user's past behaviors or characteristics. An AI/ML engine (AI-Native) can add this "personal touch" using data gathered in real-time from user interactions, or from historical data that have been accumulated over time.

- **Resource Allocation Information Exchange for Use in Optimizing Applications:** A framework to provide resource information to support the minimum service needed, as well as to relinquish resources when these are no longer required.

- **Security and Privacy Protection:** It is necessary to comply with privacy protection laws and regulations for end users. It is even more important to protect the software used in delivering experience services from malicious attacks.

6.1.3 Critical - How to Improve the Quality of Critical Roles in Sectors such as Health Care, Manufacturing, Agriculture, Transportation, and Public Safety

The Next G Alliance has assembled a library of use cases that illustrate ways to advance the quality of technology in and around health, health care, manufacturing, agriculture, and public safety with the use of robotics. Nearly every use case identifies a role for robotic-human interaction and the use of robots as a complement, both in form and function, rather than a wholesale replacement for human involvement.

Networks are likely to have a substantial role in the interface between human and robots. This relies on a combination of high bandwidth, low latency, and low jitter capabilities. Digital twin and similar capabilities will augment these capabilities, allowing humans to interact naturally with robots in the digital space and then to initiate actions in the physical world. Example applications include remote surgery, therapy, and monitoring.

The vast majority of mission-critical, network-enabled applications have similar requirements. Each seeks a combination of reliability, redundancy, dynamic allocation, and upgradability in the following critical areas:

- **Service Level:** The service level should support long-range communications such that robots covering large and diverse locations are served. Service should account for harsh environments to enable functionality above and beyond standard air communications offered today. Examples include air, land, and water machines.

- **Redundancy:** A network of autonomous robots should have redundant connectivity to the cloud to ensure connectivity remains during unforeseen events. Mission criticality depends on connectivity and cannot be lost.

- **Dynamic Service Levels:** Radio technology has evolved from hardware only to software defined. But next generations of network configuration will benefit from AI-defined configuration such that ever-changing bandwidth, latency, and jitter demands are serviced by the network dynamically.

- **Location Service:** The network shall support location information, so devices benefit from network-provided 3D positioning to complement other location technologies.

- **Upgradability:** The network shall provide standardized mechanisms for upgrades to the core, applications, and other platforms within the network.

- **Forensics Data:** As specified by the network, IoT devices shall report standardized logs and information to enable standardized data capture facilitating support and upgrades.

6.1.4 Societal Goals - How to Attain and Improve on High-Level Societal Goals

With the advent of 6G, there is a unique opportunity to consider how to address the goals of digital equity[10] and social sustainability,[6] as described in Sections 5.1.1 and 5.1.3, through applications designed to enable and encourage self-sufficiency, participation, and collaboration. For example, 6G can enable smart health care for the increasingly aging population through emerging applications and care-oriented robots that provide remote continuous health monitoring to ensure well-being. In addition, 6G communications can improve learning environments: in a school setting, on a workplace training course, or in lifelong learning through applications leveraging AR/VR providing more hands-on learning.

High-level functional requirements in support of sustainable, equitable, and inclusive societies include:

- Eliminate digital divide technical barriers by aiming for affordable universal access and ubiquitous coverage.

- Network and device requirements are needed to support basic-level tactile/visual XR/VR type of services at a lower price point to support physically challenged subscribers' wearables or assistance devices (e.g., voice, tactile, visual).

10 *https://www.digitalinclusion.org/definitions/*

» Promote ultra-long battery life capabilities for medical wearables and assistance devices.

» Increase and maintain subscribers' trust in the network and protect subscriber privacy.

6.2 Overall Summary and Recommended Actions

Various use cases that are expected to achieve the audacious goals claimed toward new business challenge and opportunity for North American and global 6G market have been discussed in four key aspects, with the focus on how they would influence humans living in the society.

Spanning from the quality of everyday living and the quality of truly immersive experience through to the quality of critical role-playing, promising 6G use cases and applications are expected to provide confidence on how new technology solutions can eventually influence the quality of humans' living in line with the Next G Alliance's audacious goals, including societal priorities for North America. Four categories define the scope of promising 6G use cases and applications. These cover aspects related to everyday living, new experiences, critical roles in health care, manufacturing, agriculture, transportation, public safety sectors, and the attainment of societal goals.

6G applications will improve the quality of everyday living, enable new experiences, support mission critical needs, and become a key factor in attaining societal goals.

A recommended outcome from use case studies on functional, performance, and value requirements, for example, should influence activities in academia and industry sectors. Ideally these should lead to a nationwide effort on cross-disciplinary and cross-industry collaborations for timely development of affordable and effective technology solutions.

7 Technology Enablers

In the approach to scoping and developing 6G systems, it is critical to address evolutionary changes and innovation in key technologies areas. These encompass new air interfaces, network architectures, spectrum access, x-haul, trust/privacy/security platforms, distributed communications and cloud, and sensing technologies.

7.1 Key Priorities and Requirements

Because there are many technology areas associated with 6G systems, the descriptions below examine critical technology elements grouped into five categories. These are:

- Component technologies
- Radio technologies
- System and network architectures (SNA)
- Operations, administration, maintenance (OAM) and service enablement (SE)
- Trustworthiness

7.1.1 Component Technologies

6G systems will raise stringent key performance requirements compared to earlier generation technologies. These will require advances in component technologies, including semiconductors, circuits and sub-systems, antennas, packaging, and testing.

7.1.1.1 Semiconductor Technology

Fundamentally, semiconductor device performance will need to be a minimum of 3x to 5x better than the wireless carrier frequency to implement radios with acceptable range, power dissipation, and link margin characteristics. For example, utilization of the sub-THz 100-300GHz spectrum will therefore require semiconductor technologies with 0.5THz to > 1THz performance.

Silicon and III-V semiconductors are candidate technologies, with advances in SiGe and InP promising >1THz performance. In addition, constraints of array lattice spacing at the smaller sub-THz wavelengths, in combination with the high losses on- and off-chip, will drive innovation in semiconductor integration, both monolithic and heterogeneous, of THz semiconductors with advanced node SOI and CMOS platforms.

Further breakthroughs in device model and simulation accuracy, Device Technology Co-Optimization (DTCO) and Systems Technology Co-Optimization (STCO) will be important to extract optimal performance and achieve first-time-right designs.

7.1.1.2 Circuits and Sub-Systems

The topic "circuits and subsystems" covers the 6G transceivers, including the front end (PA, LNA, etc.), up-/down-conversion, analog baseband, data converters, power management, and the digital circuitry for all 6G frequency ranges. As the carrier frequency moves to the sub-THz/THz range, designing the circuitry at such high frequencies with high performance becomes a challenge. Research in new transceiver architectures, circuit topologies, as well as new design methodologies in CMOS and non-CMOS (such as III-V) technologies, is required to enable high-data-rate communication for 6G while also being more affordable and sustainable.

The Next G Alliance is assessing the key 6G technology development and research areas that will impact the market.

7.1.1.3 Antenna, Packaging and Testing

Sub-components such as integrated circuits, passives (filters, inductors, capacitors, matching and tuning/switching elements), and antennas, need to be co-packaged into sub-assemblies and modules at very close proximity to address 6G technology requirements. Novel packaging, redistribution, and interconnect technology—including underlying substrate materials that allow packaging of circuits and antennas at these frequencies—need to be evaluated for extended in-service periods of use to show feasibility for consumer and enterprise applications.

Device enclosure and protective encasing technologies will affect signal transmission characteristics, implying the need for extensive research of THz-friendly enclosure materials. Thermal challenges will increase with improvement to circuit and amplifier efficiency and circuit miniaturization at these frequencies. Finally, antenna array sizing, spacing between elements, and RFIC-to-antenna routing will cause significant loss of both signal strength and power. Ultimately, to deliver products in either prototype or high-volume production, solutions are needed for verification and conformance testing, production testing, and calibration.

7.1.2 Radio Technology

6G DWEs encompass life-improving use cases such as XR, holographic communications, and service-oriented robots. They will place more stringent requirements on networks and devices in multiple areas such as data rate, capacity, latency, spectral efficiency, reliability, mobility, coverage, connection density, and energy efficiency. They will also entail innovative forms of technology fusion among positioning, sensing, and communications dimensions.

7.1.2.1 Radio Technologies for Spectral Expansion and Efficiency

Innovation in the following technologies is expected to substantially improve the KPIs that 6G systems deliver:

» **THz/Sub-THz:** The availability of multi-gigahertz of bandwidth in the THz band has the potential to enable many new applications in 6G that rely on high throughput in the multi-Gbps range.

» **mmWave Enhancements:** 5G has enabled mmWave and the deployment is expanding quite rapidly. 6G is expected to continue the evolution targeting improved coverage, robustness, and power efficiency via enhanced beamforming, beam tracking, and topology enhancements including low-cost densification.

» **Spectrum Sharing:** Bandwidth availability constraints can be alleviated for public and private networks where it is not practical to rely on only licensed spectrum.

» **Advanced MIMO Technologies:** MIMO is a key technology to improve spectral efficiency. Advanced MIMO technologies for 6G may include enhancements for lower frequency bands, massive MIMO, distributed MIMO, reconfigurable intelligent surfaces (RIS) including holographic beamforming, and orbital angular momentum, among other possibilities.

» **Advanced Duplexing Schemes:** Advanced duplexing schemes such as full duplex are expected to improve system capacity, latency, and coverage.

» **Waveform, Coding, Modulation, and Multiple Access:** Waveform, coding, modulation, and multiple access technologies are expected to continue to evolve in 6G to improve coverage and throughput, as well as spectrum, power, and cost efficiency.

7.1.2.2 Radio Technologies for AI and Distributed Cloud

AI and distributed cloud technologies are expected to play a pivotal role in 6G communications systems:

» **AI-Native Air Interface:** AI can be integrated into the design of 6G networks, potentially yielding performance gains and cost reductions compared to 5G networks. The large amount of data generated by networks can be leveraged for training/testing models for an AI-Native 6G air interface.

» **Air Interface Enablement for Distributed Computing and Intelligence across Device and Network:** Efficient air interface features and protocols with awareness about the distributed computing and intelligence functions should be studied to limit the impact of imperfect radio channel conditions.

7.1.2.3 Radio Technologies for Green Communications

Energy-efficient communications is a key goal of 6G systems, which will be characterized by higher numbers and permutations of carriers, antennas, ports, densification, and use cases, among other factors:

» **Green Network:** Energy-efficient networks will involve dynamic adaptations in time, frequency, and space (Tx/Rx chains/port), PA efficiency, AI/ML assistance, energy-efficient signals, and protocol design.

» **Device Power Saving:** Device power-saving techniques considers power vs. performance trade-off, joint power optimization across device and base station, and cross-layer power consumption optimization.

» **Zero-Energy Communications:** Zero-energy communications technologies allow base stations or devices to communicate with extremely low or net-zero energy.

» **Ultra-Low-Resolution Communications Systems:** Low-resolution communications techniques for systems with large bandwidth, high sample rates, and large number of antennas can lead to savings in both power consumption and component costs.

7.1.2.4 Radio Technologies for Advanced Topology and Networking

Support of the diverse and integrated network topologies expected for 6G (Section 7.1.3.1) will call for research into new requirements on topics related to radio technologies for mesh networks, device-to-device communications, cooperative communications, non-terrestrial communications, and radio for extreme networking. Research will also be required to enhance radio technologies for 6G applications in the industrial domain and to support in-vehicle, in-body, and intra-body, seamless mobility deployments.

7.1.2.5 Radio Technologies for Joint Communications and Sensing (JCS)

Recognition of the surrounding environment takes on a heightened importance in new and promising commercial and industrial domains. These include the smart home, factory, cities, and highways. Sensing of the environment is also important for interactive gaming, automotive safety, health care, industry automation, and RF surveillance applications.

Wireless sensing and positioning encompass a wide range of functions and technologies. This begins with basic functions such as determining the distance, angle, and velocity of objects. Advanced functions include imaging and 3D mapping capabilities. Proprietary technologies such as depth camera, lidar, and radar are widely used to provide such functionalities. However, for a more seamless and efficient evolution, it is desirable to reuse and extend existing technologies and resources for data communication to enable wireless sensing and positioning. JCS technologies will extend the capabilities associated with positioning functionality.

Radio technologies for JCS will involve MIMO sensing, RIS-aided sensing, RF sensing, UE-centric sensing, base station centric sensing, cooperative sensing, duplexing schemes, new waveforms, and spectrum sharing between communications and sensing.

7.1.3 Systems and Network Architectures

6G is expected to become more integrated into not just our daily lives, but also the power, transportation, agriculture, and similar infrastructure systems that our lives depend on. This means that the scope of 6G will expand well beyond the traditional concept of a terrestrial cellular network. Technological innovations are required to allow this expansion, as described below.

7.1.3.1 Network Topologies

6G is expected to evolve beyond traditional cellular networks, supporting diverse and integrated network topologies to address a wide range of use cases and deployment scenarios. It also is expected to continue the trend of supporting satellite-based networks. In addition, it is expected that users in the future may not include just terrestrial devices but also drones and aircraft. Satellite and aeronautical systems have evolved differently from cellular systems due to different business models and different technical constraints. To support interconnectivity of these technologies, and to do so in a manner that leverages some of the economies of scale, will require further work to understand the necessary compromises and advances. Examples of these areas include the increased distances, high relative speed, and different spectrum regimes.

In addition, it is expected that the traditional hub-and-spoke architecture associated with cellular networks will continue to diversify. While 3GPP has already started heading down this path with sidelink, relays, and IAB, 6G is expected to continue that trend. However, advances are needed in both sidelink and in network support of mesh topologies to allow 6G to function efficiently in a dynamic network of user devices. In addition, there are significant challenges related to privacy and resource usage as communications passes through mesh nodes.

7.1.3.2 Network Adaptability

As 6G is expected to fill more market niches, even more deployment flexibility is required. Some of the initiatives in this direction include:

- Solutions based on disaggregation that split functionality into smaller open components. This allows for mixing and matching of components while increasing the potential for virtualization.
- Embedded sub-network connectivity allowing devices to maintain services and discover new services even as they transition in and out of fully or partially isolated subnetworks.
- New open network frameworks and APIs expanding ways in which 6G can fulfill new use cases.

7.1.3.3 Distributed Cloud and Computing

6G must address use cases involving tight, real-time requirements. To meet these requirements, it is necessary to consider not only the communications, but also the computing that must occur between the request and responses. This research area investigates the 6G system architecture and features for a distributed cloud framework, where computing and data resources/services are distributed in devices, network nodes, and data centers. This contrasts with present-day cloud computing where computing and data resources/services reside in a few national and regional data centers. A tight integration between communication, computing, and data is expected to enable distributed cloud in a wide-area system. Computing plane and data plane resources and services are expected to become integral components of 6G system in addition to communication plane services and resources.

Treating computing and data as resources within a communications system will require new concepts for how to deal with associated issues.

7.1.3.4 AI in Networks and Devices

Within the 6G networks and devices, many functions have been identified where AI/ML can enhance and optimize functionality. Examples of this include:

- AI-based PHY/MAC
- AI-assisted mobility
- AI-optimized resource allocation
- AI for orchestration
- AI for security

How to apply AI to each of these areas will require further research. In addition to how AI is being used in 6G, there are also general principles related to AI and associated data that must be considered such as explainability, predictability, and freedom from bias. Understanding these requirements in the context of how they are to be used in 6G is also a needed area of research. In addition, 6G is expected to include various sensing technologies. The ability to sense the environment when coupled with AI is expected to lead to ambient intelligence. This ambient intelligence allows the creation of embedded, context-aware, personalized, adaptive, and anticipatory user interfaces.

7.1.4 Network Operations, Administration and Management, and Service Enablement

Network OA&M and SE are important research and development areas to maximally exploit the advantages of cutting-edge, 6G radio and core network design. For instance, the underlying technologies can provide a means to operate, administer, and manage a 6G network more efficiently and reliably via zero-touch, end-to-end automation. They can also reduce energy consumption and generate OPEX savings.

6G is also posed to enable various new services across industry sectors, governments, and organizations to fulfill their unique needs including providing more secure and reliable connectivity for public safety personnel, or first responders acting in emergencies and disasters. While these sectors have key distinguishing requirements, they also have a universal interdependence that, when realized, will enhance the services available to all. For example, public safety and business both depend on robust service management/orchestration, as well as an energy-efficient platform in order to maximize the service availability when the network is stressed due to network outages or traffic overload during a disaster.

7.1.4.1 Service Management/Orchestration, Data Management, and AI/ML-Based Intelligent Network Controller for Automation

6G will shift the network OA&M from being manually controlled to an inherently intelligent, zero-touch operation. In the current 5G network, AI tools are being developed separately for particular use cases. This can be viewed as a bolt-on solution to the existing network. In contrast, with 6G systems, AI can be built-in to the design of the network itself to support native, end-to-end AI.

6G networks can also support AI/ML lifecycle management in areas related to data preparation, modeling, AI operations, policy/intent enforcement, and enrichment of data collection. To this end, there are 6G research opportunities to enhance the service management and orchestration framework, data management frameworks, and intelligent network control and automation frameworks. Interactions between management plane functions, control plane functions, and air interface should be also considered.

7.1.4.2 Public Safety in Emergencies and Disaster Scenario

6G systems should take on an elevated level of criticality when public safety personnel or first responders are acting in emergencies and disasters. Connectivity is currently made available through networks comprising land-mobile, cellular, and dedicated private radio systems. The present-day level of integration of these elements is highly variable. It results in routine gaps in remote support and situational awareness on the part of the first responders, remotely situated management, and support staff. 6G provides an opportunity to bring technologies to bear securely and more reliably, thereby enhancing the operational picture for extended first responder teams. In this regard, future research is warranted in areas that will allow 6G systems to provide secure discovery of network peers, facilities, and clients, to secure proxy services, to enable secure and dependable geolocation, and to assure the quality of experience (QoE).

7.1.4.3 Technology Enablers for Business Services Convergence

Technology enablers allow organizations to harmonize, synchronize, integrate, visualize, federate, and analyze data to power digital transformation and develop new value-added services. They can also enhance older technologies and applications. The broad principle of designing 6G is to build a platform of reusable technologies progressively and to establish a cohesive framework of projects to collect common services over time. Areas for future research are in technologies for a shared foundational orchestrator of common services such as secure communications and distributed cloud services. Examples of such research areas include natural language processing for simple and federated searches, autonomous systems, and exposure interfaces for network performance, among others. The scope of this work is likely to focus on a horizontal platform orchestrator model with clearly categorized components for service convergence.

7.1.4.4 Energy-Efficient Green Network

The 6G OA&M should provide a means of running cellular networks more energy efficiently. To this end, 6G should provide tools for monitoring energy consumption, analytics, and controls to reduce the energy consumption of the overall network. Enabling technologies include zero-touch network automation, AI-based solutions for energy-efficient network operation, and deployment.

7.1.5 Trustworthiness

Trustworthiness is one of the Next G Alliance's audacious goals as described in Section 3.2. Furthermore, it is expected that 6G will become a more integral part of everyday life and the infrastructure that society depends on. This means that security, reliability, resilience, and privacy become even more important and reliant on the following technologies to ensure that 6G systems are trustworthy.

7.1.5.1 Communications Security

Secure communication is fundamental to all generations of mobile communications. However, this is not a static measure of performance. As adversaries and tools become more capable, so must the communications network.

PHY/MAC security provides an additional level of security and privacy to complement traditional encryption techniques. These techniques make use of characteristics of the radio environment, as well as the network topology. Potential examples of such techniques are:

- Specially designed beamforming and MIMO precoding methods.
- Procedures to generate encryption keys and to authenticate users based on the intrinsic randomness of the radio channel.
- Symmetrical key generation based on fingerprinting.

In addition, PHY/MAC techniques can be used to address jamming and spoofing attacks.

Anticipated advances in quantum computing mean that the design and deployment of 6G systems must prepare for a post-quantum security era. Much of today's public-key cryptography infrastructure will need to be replaced by post-quantum cryptography (PQC) to ensure that algorithms can resist cryptanalysis carried out by quantum computers. In addition to just viewing quantum computing as a threat, it can also be used to enhance security through techniques such as:

- **Quantum Key Distribution (QKD):** Exploiting quantum mechanics to generate and distribute keying material.
- **Quantum Cryptography (QC):** Using quantum mechanics to protect a communications channel.

7.1.5.2 System Reliability

6G systems must be dependable along reliability and availability dimensions in the face of failures (both software and hardware), attacks (both malicious and accidental), and disasters (manmade or natural). There are challenges in ensuring that a system that is both more flexible and distributed is also more trustworthy.

Automated, closed-loop security is needed where the network detects failures and attacks and takes mitigation measures. This calls for research, systems engineering, and operational validation activities on how to measure and identify abnormal events, as well as techniques to respond rapidly. AI will be critical in the analysis and response to threats. Similarly, there is likely to be a reliance on service availability enablers and feedback loops to leverage reconfigurability, redundancy, diversity, and pooling to ensure that sufficient resources are available to meet SLAs.

Security assurance and defense expands the concept to the entire 6G lifecycle. Security must be maintained during development, deployment, and operations of networks. As before, AI is expected to be influential in security assurance.

7.1.5.3 Safeguarding Data and Privacy

6G will be more flexible in terms of how computation and data are distributed throughout the network. There is a need to protect AI models, the data that they consume, and the results they produce. Research is required into confidential computation and storage techniques to address how data, algorithms, and proprietary AI models can be accessed and secured in a distributed cloud and communications environment.

Data provenance deals with ensuring the integrity of data and associated metadata in 6G systems. The associated metadata governs how the data can be used, moved, changed, and destroyed. This may entail the use of technologies such as blockchain, chains of trust, and secure environments.

These different aspects of security are needed not only for trustworthy computation, but also for the preservation of privacy.

7.2 Overall Summary and Recommendations

6G represents a new paradigm in communications because of advances in communications and sensing, convergence of communications and compute, higher targets for hardware density and data throughput, and more rapid decision making through automation and native-AI capabilities. Research, systems engineering, and operational validation efforts on technologies for 6G should focus on the following five technology areas that have been described in this section: component technologies; OA&M and SE; radio technologies; system and network architectures (SNA); and trustworthiness.

8 Spectrum

8.1 Key Priorities and Requirements

Current spectrum-access frameworks are based on a well-structured approach to meeting spectrum needs using licensed, unlicensed, and shared regimes. They have successfully supported mobile applications and will remain an important requirement. These applications and markets will support national imperatives: security, sustainability, economic growth, connected society, and technology leadership.

> The Next G Alliance will study and assess spectrum suitability for 6G needs, and evaluate spectrum management and access mechanisms needed to maximize North American 6G opportunities, and to formulate a regulatory policy roadmap.

Based on an initial assessment, there are three key priorities identified related to spectrum for 6G systems:

1. Study and assess potential 6G suitable spectrum bands based on applications and technology requirements, including required bandwidth/amount of spectrum. This study will include such aspects as:
   - Application performance requirements.
   - Use case characteristics.
   - Enabling technologies.
2. Evaluate the range of spectrum management and access mechanisms needed to maximize North American 6G opportunities while promoting the most effective and efficient spectrum uses, including licensed, unlicensed, and shared.
3. Assess regulatory policy changes/initiatives that will impact North American 6G industry competitiveness. This assessment will include the:
   - Identification of potential licensing models/regimes spanning licensed, unlicensed, shared, and others.
   - Creation of a set of recommendations that can be shared with industry and government stakeholders for actionable implementations in policy.

8.1.1 Priority 1 – Identification of Spectrum Suitable for 6G Services

The Next G Alliance has been working diligently on the first priority. Based on inputs received so far, we have developed the scope for developing a consensus-based position on the study of potential 6G spectrum bands including the amount of spectrum required in various spectrum ranges and deployment scenarios. The scope includes, but is not strictly limited to:

- **Terminology:** Definitions related to spectrum nomenclature commonly used in regulation.
- **Summary Status of 3G/4G/5G Spectrum:** Information about the status of various spectrum bands that are either used or could be used by 6G. The focus is on North America but information, if any, about globally harmonized spectrum might also be included.
- **Technical, Operational, and Usage Elements of 6G-Affecting Spectrum:** Aspects of technology, operation, and use of 6G systems that have direct impact on spectrum needs of 6G, both from the amount of spectrum and the spectrum range point of view. Examples will likely include target KPIs for various envisaged applications and deployment models considered. This information is intended to inform the derivation of spectrum needs for 6G.
- **Methodologies for Calculating Spectrum Needs of 6G:** These are both in terms of the amount and possible spectrum ranges. They could be based on traffic growth, application KPIs, or any other proposed methods.
- **Assessment and Derivation of 6G Spectrum Needs:** Targets for technical, operational, and usage elements to the methodologies for calculating spectrum needs, with the aim of arriving at the results for the expected spectrum needs for 6G.
- **Potential Spectrum Ranges/Bands to Study for 6G:** Identification of suitable spectrum ranges and potentially a narrowed down list of spectrum bands resulting from analysis identified in this priority.
- **Technology Enablers Affecting Spectrum Availability:** Summary of the technology elements that could help with making additional/new spectrum available for 6G, with a focus on availability of those ranges identified for potential study. These technologies could include various trends related to spectrum sharing, distributed intelligence, etc.

As 6G applications are identified, various approaches can be used to assess spectrum needs, such as consideration of application performance requirements in relation to traffic characteristics. For example, methodologies based on application and other technical performance attributes could be considered as more applicable than traditional traffic-based approaches. All spectrum ranges should be considered because each spectrum band presents different perspectives and usage models to provide coverage, capacity, performance, and support for new services. Information on the nature of potential use cases, applications, environments, and other technology and deployment related information will have impact on spectrum needs.

Figure 8.1 describes the process to identify suitable spectrum for 6G based on inputs received from other working groups. Arriving at suitable spectrum ranges/amounts for 6G would be supported by technical and regulatory analysis, which ideally produces one or more of the following:

- Estimate of the total amount of spectrum needed for 6G.
- Possible division based on frequency ranges.
- Possible division based on environment/geography.

The Next G Alliance will also attempt to identify suitable spectrum ranges, including existing 4G/5G spectrum, to arrive at new spectrum needed for 6G, including ranges and amounts. It is expected that the results of this process will be included in the submission to IMT-2030.

8.1.2 Priority 2 – Spectrum Management and Access Mechanisms

Developing a forward-looking approach to evolving spectrum management and access to maximize 6G opportunities while promoting the most effective and efficient spectrum uses is key to ensuring North American competitiveness.

8.1.3 Priority 3 – Regulatory/Policy Factors to Enhance North American Competitiveness

Assessing regulatory policy changes/initiatives that will impact North American 6G industry competitiveness includes consideration of possible innovative licensing models and regimes. The goal will be to create a set of recommendations related to forward-focused spectrum management that can be shared with industry and government stakeholders for actionable implementations in policy.

8.2 Impact of Applications and Technologies on Spectrum

Section 6.1.1 indicates that high-level requirements associated with envisioned usage scenarios include the ability to support higher data rates. This points to the potential need of new spectrum bands or new modes of spectrum usage to support higher data rates and lower latency for new 6G applications (e.g., holographic communication).

Additional spectrum demands could also stem from supporting current 5G applications (e.g., XR, 8K video) at larger scale as evolving device technologies will enable wider commercial adoption and deployment of such applications. The nature of future heterogeneous data is expected to drive value in verticals such as entertainment, financial services, and defense. Greater knowledge and control of timing and latency will allow support of isochronous parallel data channels from multiple sources, thus allowing levels of synchronicity that have not been available in wireless systems. Any application focused on synchronicity of data capture and delivery will benefit from synchronous, heterogeneous, and parallel data channels, driving spectrum requirements.

8.3 Overall Summary and Recommended Actions

The next steps involve developing and assessing KPIs for 6G use cases and technical elements. This information will be applied to the methodology developed under priority 1 to derive an estimation of 6G's total spectrum needs. The methodology is expected to produce a total amount, as well as more granular information (e.g., on spectrum needs per environment and/or use case, contiguous/non-contiguous). Suitable spectrum ranges for implementation of 6G can then be narrowed down as much as possible to arrive at specific frequencies.

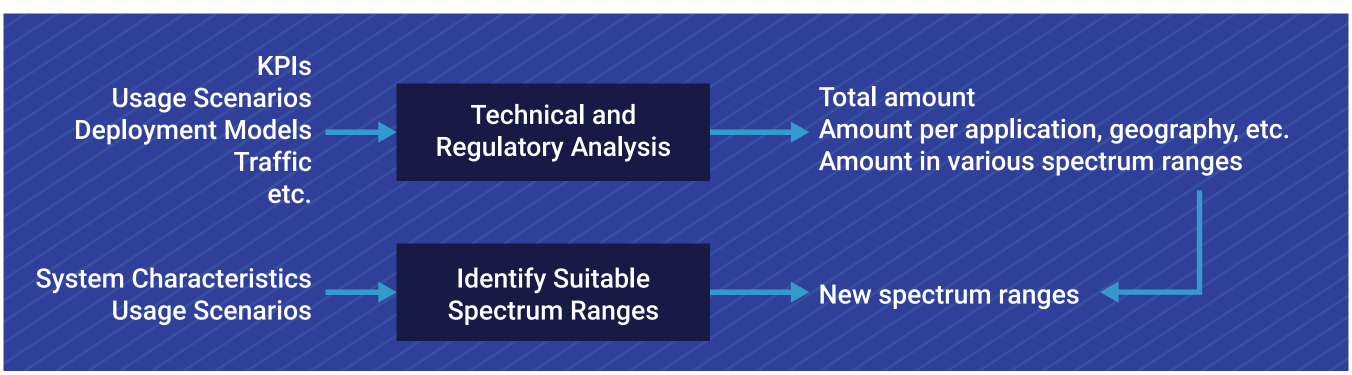


Figure 8.1: Arriving at 6G Spectrum Needs

9 Environmental Impacts

The Next G Alliance seeks to position North America as the global leader in environmental sustainability in future generations of wireless technology or "Green G." This section describes the key priorities and requirements toward this objective.

9.1 Key Priorities and Requirements

As the computing and telecommunications industries evolve towards the deployment of 6G systems, they face three key priorities to reduce their carbon emissions and overall environmental impact: Reduced CO2 and GHG emissions, better use and re-use of raw and rare materials by means of circular economy principles, and better use of land and water resources. To help industry actors transition to a more sustainable 6G, targets and incentives for each of these three factors need to be put in place. The efforts to protect the environment can further be amplified by influencing and equipping other industries with innovative capabilities that have the potential to reduce their own emissions and impact.

9.1.1 Reductions in CO2 and GHG Emissions

According to the ITU, the ICT sector has already committed to reducing GHG emissions by 45% from 2020 to 2030.[11] Looking ahead to 2040, there is a need to establish Scopes 1, 2, and 3 categories of Science-Based Targets (SBTs) for the ICT industries. Scope 1 includes direct GHG emissions that an organization makes. Scope 2 covers indirect emissions such as energy purchases for heating and cooling buildings. Scope 3 includes all the emissions that an organization is indirectly responsible for, up and down its value chain. This is where the ICT industry can influence and help other industries achieve net-zero GHG emissions prior to 2050, targeting 2040 or sooner. The externalities associated with GHGs make it even more important to educate and share details about energy consumption and lifecycle GHG emissions with end users. This will help them to make informative purchasing, usage, and disposal decisions. The key requirements to address these priorities involve:

- » Encouraging each North American operator and ICT vendor to commit to SBTs and achieve net-zero GHG emissions by 2040 or sooner.
- » Defining common metrics to be collected and shared with end users.
- » Collecting, monitoring, and publishing progress on an annual basis with consistent targets and metrics across the industry.
- » Stimulating innovation and development of alternative solutions with government funding or tax incentives.

Achieving Green G sustainability goals requires strong commitment from the industry, the development of new international standards linked to common metrics, expanded research, and educational measures that drive more responsible behaviors.

9.1.2 Improvements from Better Use of Raw Materials, Batteries, and Circular Economy Principles

There are several priority areas to reduce the environmental impact of 6G systems. These include optimizing design and manufacturing activities, both for processes and materials, and approaches to maximize energy efficiency. There is also scope to minimize or substitute for the use of raw materials, notably rare, virgin, limited, or non-renewable materials (natural resources). The large market potential for battery-powered devices means that efficiency solutions represent an important energy conservation strategy. Consideration of the full lifecycle of 6G systems and components will call for processes to recycle and reuse waste materials, which will help toward better resource consumption and reduced pollution. The key requirements to address these priorities involve:

- » Conduct life cycle assessment (LCA) to measure environmental impacts.
- » Set priorities and consider options during planning and design based on expected impacts (part of the decision process).
- » Use of sustainable procurement practices.
- » Incentivize recycling and reuse of materials.
- » Define targets for network equipment and device recycling rates.
- » Stimulate research to enable rare, virgin, limited, or non-renewable material replacement.
- » Stimulate research to enable more efficient energy storage and retrieval, including battery technology.

11 *https://www.itu.int/en/mediacentre/Pages/PR04-2020-ICT-industry-to-reduce-greenhouse-gas-emissions-by-45-percent-by-2030.aspx*

9.1.3 Better Use of Land and Water Resources

The operations of ICT ecosystem organizations have a bearing on various environmental resources such as the air, water, and land. A first step in developing environmental mitigation solutions is to understand and quantify the impact of how land and water are used and recycled. Such an assessment would range from usage patterns in data centers and other cooling infrastructures, for example, to manufacturing activities related to network and device classes of equipment. The key requirements to address these priorities involve:

- » Define network equipment and devices on green credentials.
- » Define targets for volumes of water being used.
- » Define solutions and targets for water reuse and water efficiency metrics.
- » Define targets for appropriate site location with respect to water availability.
- » Define targets and measure land surface being occupied.
- » Define targets and measure land and water pollution or environmental impact (dryness, heat, etc.).

9.2 Resulting Design Enhancement for 6G Systems

There are environmental impact gains to be made in distinct parts of telecommunications networks. In the RAN, the challenge is to reduce energy consumption. In the core network, the challenges involve optimizing resource allocations and usage to reduce energy consumption. In the data center, there is potential to reduce the environmental impact in areas related to land, water, and materials use, as well as architectural approaches to evolve to net zero on distributed data center (edge and cloud) configurations. Network management and operations capabilities provide flexible tools to measure, analyze, and optimize resource allocation. They facilitate workload placement and help to reduce energy consumption. In terms of devices connecting to 6G systems, there are opportunities to reduce energy consumption and to evolve to zero-energy devices. In addition to the component approach, there are opportunities to apply end-to-end principles, making energy consumption a first-class metric throughout the network. The use of APIs can also facilitate access to detailed, real-time reports about which parts of the network consume how much energy.

9.3 Overall Environmental Impact Summary and Recommended Actions

In summary, there is a need to implement several critical changes between now and the release of 6G systems. Their aim is to preserve our planet and to sustain an economy and service offerings around mobile communications.

An initial assessment highlights several requirements and associated actions in three key sustainability dimensions, namely reduced CO2 and GHG emissions, better use and re-use of raw and rare materials by means of circular economy principles, and better use of land and water resources. Their adoption will require strong commitment from key actors in this industry, including network operators, large vendors, and government agencies. They will also depend on the support of the research community and the endorsement of end users.

To best achieve standardization and adoption of common methods, it is important that ICT companies utilize, maintain, and drive the development of new international standards in support of common metrics and methods such as those listed above.

Education is also required to build common knowledge and understanding and to drive the transition to more responsible behavior across the value chain. The success of these initiatives will require investments in more sustainable product and services design.

Appendix A: Definitions and Abbreviations

A.1 Definitions

III-V compounds	Chemical compounds with at least one group III (IUPAC group 13) element and at least one group V element (IUPAC group 15), e.g., Gallium Nitride (GaN) and Indium Phosphide (InP). IUPAC is the International Union of Pure and Applied Chemistry.
AI-Native	Systems that have AI capabilities designed for or built into from the beginning.
Availability	Refers to the time the network or system is operational for use.
Carbon neutral	A company's carbon emissions are reduced as much as possible and then balanced by offsets.
Cloud native	Systems have cloud capabilities designed for or built into from the beginning.
Digital World Experience	A multi-sensory experience that transforms human interactions including human-machine and related machine-machine communications across physical, digital, and biological worlds.
Resiliency	Refers to the ability of a network or system to provide an acceptable level of service to users despite any faults or outages.
Sustainability	Refers to developing the network or system in an ecologically sound, socially just, and economically viable means.
User plane protocols	Enable transfer of user data in a network.
Control plane protocols	Control the connections and the flow of user data between devices in a network.
Management plane protocols	Enable configuration, administration, and management of the network.
Computing plane protocols	Enable control/management of and access to computing resources and services distributed within a network.
Data plane protocols	Enable management of and access to data distributed within a network.

A.2 Abbreviations

AI	Artificial Intelligence
API	Application Programming Interface
CAPEX	Capital expenditure
CMOS	Complementary Metal-Oxide-Semiconductor
CPE	Customer Premise Equipment
CSP	Communication Service Provider
CSR	Corporate and Social Responsibility
CV2X	Cellular V2X
DL	Downlink
DoS	Denial of Service
DWE	Digital World Experience
eMBB	enhanced Mobile Broadband
GHG	Greenhouse Gas
ICT	Information and Communications Technology
IIoT	Industrial IoT
IMT	International Mobile Telecommunications
InP	Indium Phosphide
IoT	Internet of Things
KPI	Key Performance Indication
LNA	Low-Noise Amplifier
MIMO	Multiple-Input, Multiple-Output
ML	Machine Learning
OPEX	Operational Expenditure
OSI	Open Systems Interconnection
PHY	Physical (Layer)
QoS	Quality of Service
R&D	Research and Development
RAN	Radio Access Network
RF	Radio Frequency
RRH	Remote Radio Head
RRM	Radio Resource Management
SDK	Software Development Kit
SiGe	Silicon Germanium
SOI	Silicon-On-Insulator
SLA	Service Level Agreement
UE	User Equipment
UL	Uplink
URLCC	Ultra-Reliable Low-Latency Communications
V2X	Vehicle to Anything (communications)
WAN	Wide- Area Network
XR	eXtended Reality

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