Communications Technology Laboratory

6G Communications Roadmap

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NIST COMMUNICATIONS TECHNOLOGY LABORATORY

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Executive Summary

The National Institute of Standards and Technology (NIST) Communications Technology Laboratory (CTL) developed the 6G Communications Roadmap (the roadmap) to prioritize future NIST investments in 6G Communications research that aligns with high-priority stakeholder needs and is in line with CTL's mission: "*Advance connectivity. Enhance performance. Grow our economy. Improve lives.*"

The roadmap charts a path for its internal research efforts to maximize CTL impact given anticipated trends, innovations, and activities across the 6G communications research and development (R&D) domain. Six months of external stakeholder engagement sessions informed NIST research goals grounded in tractable science and aligned with current CTL capabilities and growth strategy. This engagement with key stakeholders produced five specific goals for CTL research into 6G communications over the next five to seven years.

Why 6G Communications

6G communications represent the next major advancement in wireless technology, offering faster speeds, lower latency, increased capacity, and improved connectivity beyond 5G. Building on 5G, 6G incorporates new technologies, such as integrated sensing and communication, open network architectures, Artificial Intelligence and Machine Learning applications, and advanced hardware solutions.

These innovations enable ultra-fast data transfer, real-time responsiveness, high bandwidth, and support for emerging applications such as autonomous systems, industrial control, and space connectivity. CTL leads efforts to develop these technologies, conduct spectrum research, and foster industry collaboration. CTL works on closing 6G metrology gaps, enhancing security and resilience of networks, automating network management, building testbeds, and advancing measurement and sensing capabilities.

High-Level R&D Goals for 6G Communications

The 6G Roadmap defines five goals, listed without specific order, for CTL research to influence 6G Communications over the next five to seven years. Each goal addresses stakeholder-identified needs within the 6G Communications community to drive innovation and deliver creative solutions to complex communication challenges.

Goal 1: Enable AI-Native 6G Applications

CTL will develop high-quality datasets for training, baselining, and benchmarking Artificial Intelligence (AI) applications in 6G networks, thereby facilitating the smooth integration of AI across all operational layers, from physical transmission to service management. The effort focuses on creating trusted, accessible datasets to enable real-time, adaptive AI models. NIST's leadership and infrastructure will support interoperable, reproducible, and secure data sharing that advances AI-native network capabilities. CTL's impact will accelerate innovation, improve network performance, and enable robust AI implementations across the 6G ecosystem.

Goal 2: Enable Sensing

CTL will develop standardized sensing and communication capabilities integrated into 6G networks to enhance public safety and mission-critical applications for the U.S. government. The focus is on creating validated measurement methods, modeling platforms, and testbeds to accurately assess sensing performance across various network deployments and environments. CTL will establish reliable performance metrics, open-source tools, and data fusion techniques to improve network optimization. These efforts aim to enable interoperability, reliability, and trustworthiness among vendors and deployments, which will facilitate the widespread adoption of sensing-enabled 6G networks.

Goal 3: Make 6G Systems More Robust and Resilient

CTL will enhance the robustness and resilience of 6G systems for mission-critical applications, including government and public safety. These efforts will improve hybrid terrestrial and non-terrestrial network integration, reliable device-to-device communications, and maintenance of connectivity during emergencies. Standardization and testing led by NIST will ensure that 6G systems can operate effectively in challenging environments. The focus is on ensuring 6G's reliability and interoperability for commercial, safety, and defense operations.

Goal 4: Make 6G Infrastructure Secure

CTL will develop a secure 6G infrastructure for government, public safety, and critical applications. It emphasizes enhancing existing security techniques to address new 6G-specific technologies like AI-native functions and integrated sensing. The focus is on creating flexible, resilient security standards that adapt to emerging use cases such as immersive communication and cyber-physical system integration. CTL will contribute to the establishment of cybersecurity frameworks, including Zero Trust principles and quantum-safe cryptography. CTL's research will enable a robust, secure, and adaptable 6G network ecosystem supporting diverse and mission-critical applications.

Goal 5: Validate Performance of 6G Hardware

CTL will develop measurement, modeling, and calibration techniques to validate 6G hardware performance, particularly in high-data-rate scenarios. Approaches focus on accurate characterization of high-frequency materials, calibrations and measurements to quantify signal distortion over wide bandwidths, and accurate evaluation of antenna parameters for implementing multi-antenna techniques. Key deliverables include SI-traceable methods and calibration services for devices and materials from DC to sub-THz, new metrics for characterizing low distortion levels in broadband systems in both the frequency and time domain, and validated testing for next-generation multiple antenna systems. Through these efforts, CTL will reduce design uncertainty, lower costs, and improve energy efficiency, enabling faster innovation, reliable validation, and standardized practices. It aims to make 6G systems scalable, cost-effective, and high-speed for commercial and critical uses.

Each goal addresses stakeholder-identified needs within the 6G Communications community to spur innovation and deliver creative solutions to complex communications challenges.

Introduction

The National Institute of Standards and Technology (NIST) Communications Technology Laboratory (CTL) developed six roadmaps to guide its internal research and development (R&D) efforts over the next five to seven years to prioritize future NIST investments that align with high-priority stakeholder needs and are in line with CTL's mission: "*Advance connectivity. Enhance performance. Grow our economy. Improve lives.*" Each roadmap highlights CTL's current capabilities, strategic R&D planning and resourcing, and additional opportunities for advancing communications technology, architecture, and research. CTL chose the following areas to focus road mapping efforts:

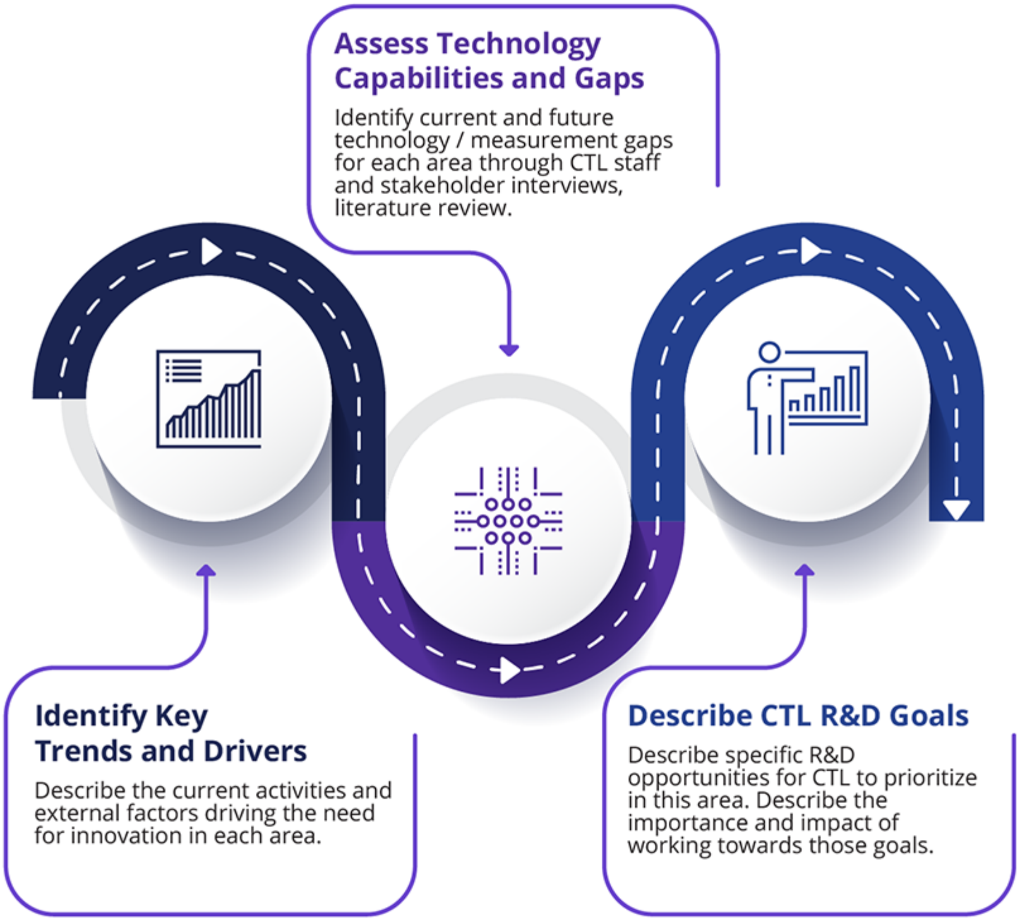
- 6G Communications
- Spectrum Science
- Quantum Communications
- Radio Frequency (RF) Metrology and Calibrations
- CTL in Space
- Public Safety Communications Research

By developing these roadmaps, CTL aims to achieve the following:

- Focus CTL resource allocation on the highest-priority measurement science, technology, and standards needs affecting stakeholders.
- Illuminate emerging technology areas and external factors affecting CTL research.
- Identify the skill sets and lab capabilities to prioritize through recruitment and procurement.
- Clarify the R&D topic areas that CTL should prioritize, given the activities of other stakeholder organizations and NIST's unique mission and capabilities.
- Substantiate CTL decision-making through external communications and stakeholder engagement.
- Establish a common language for CTL to describe its operating environment, technological needs, and R&D opportunities.
- Create a framework illustrating the criteria, rationale, and expected impact of CTL R&D.
- Expand collaboration efforts with stakeholder organizations focused on identified joint 6G research goals.

This roadmap charts a path for maximizing CTL impact given anticipated trends, innovations, and activities across the 6G communications R&D domain.

The document includes an Introduction that outlines the purpose, definitions, and methodology used for this effort; a review of Key Trends and Drivers influencing 6G communications-related research; an analysis of 6G Communications Gaps; and Goals and Implementation Pathways describing the factors motivating 6G communications research and the strategies for addressing identified gaps. The Appendix lists contributing participants and identifies additional 6G communications gaps that were discussed but not included as main gaps for this roadmap's priority CTL R&D goals. Each section offers detailed insights into the findings and analysis that support the roadmap's structure and direction.



Identify Key Trends and Drivers

Describe the current activities and external factors driving the need for innovation in each area.

Assess Technology Capabilities and Gaps

Identify current and future technology / measurement gaps for each area through CTL staff and stakeholder interviews, literature review.

Describe CTL R&D Goals

Describe specific R&D opportunities for CTL to prioritize in this area. Describe the importance and impact of working towards those goals.

6G Communications Roadmap Definitions

6G communications represent the next frontier in wireless communications, delivering transformative advancements in speed, latency, capacity, and connectivity that surpass current 5G networks. 6G builds upon 5G by embracing new technologies, including integrated sensing and communication, advanced open network architectures, AI and Machine Learning (ML) applications for communications, and innovative hardware architectures such as advanced antenna systems. It also examines security, spectrum science, edge computing, sidelink technologies, and Internet of Things (IoT) integration while addressing data availability, privacy, and usage.

These innovations enable ultra-fast data transmission, real-time responsiveness, high bandwidth, and seamless support for emerging applications such as autonomous systems, industrial control systems, and space-based connectivity. CTL leads the development of technologies and measurement and evaluation capabilities, such as channel propagation and modeling, conducts spectrum science research, and fosters industry collaboration to support 6G communications systems.

Specifically, CTL is addressing 6G metrology gaps and contributing to standards development through enhancing internet and Open RAN security and resilience, investigating novel approaches to automate and optimize network management, building a 5G/6G testbed, developing next generation of channel measurements and propagation models, developing and evaluating sensing capabilities, and advancing core and end-to-end services. Through these projects, which drive innovation and improve network connectivity, CTL ensures reliability, accessibility, and security for next-generation wireless networks.

Methodology for Roadmap Development

CTL implemented a multi-phase strategic planning approach from November 2024 to May 2025 to guide the development of the research roadmap. This approach included internal coordination, rigorous analysis, and structured engagement with external stakeholders. Three strategic planning sessions provided the foundation for roadmap development. Strategic Planning Session One, held in November 2024, established the overarching framework, identified five priority topic areas, including 6G Communications, and set a timeline. In February 2025, Strategic Planning Session Two focused on defining CTL's external stakeholder engagement strategy and refining research gap lists. By May 2025, Strategic Planning Session Three concluded the internal planning cycle by finalizing R&D goals, aligning resource requirements, and identifying cross-cutting strategic themes across each roadmap topic area.

Point of Contact (POC)	Subject Matter Experts (SMEs)	External Experts
Points of Contact, or POCs, are responsible for roadmap development and review. These individuals are the final decision-makers for their specific topic area and are experts within the field. POCs are current Division Chiefs or NIST Fellows.	Subject Matter Experts, or SMEs, are internal CTL staff who have a breadth and depth of knowledge within the topic area.	External Experts are highly regarded within their field, have an established relationship with NIST, understand industry need, and are well versed in advances needed within the topic area. External Experts represent academia, industry, and government entities such as Federal agencies or Federally Funded Research and Development Centers.

To build a robust foundation for these discussions, CTL conducted a literature review and internal interviews to document current capabilities, identify technical gaps, understand prior research efforts, and discuss opportunities for future research. This work drew directly from CTL's publication NextG Communications Research and Development Gaps Report (NIST SP 1293), which has a catalog of over 100 wireless communications research gaps. This internal baseline ensured that subsequent stakeholder engagements would be well-informed and focused on priority areas for industry, academia, and government partners. Using this foundation, CTL held a comprehensive panel discussion that successfully addressed all three external engagement objectives: validating existing R&D gaps, prioritizing them based on urgency and impact, and identifying emerging research opportunities. This streamlined approach reflected both the maturity of the initial gap analysis and the depth of expertise among participants. The panel featured subject matter experts from industry and academia with strong familiarity with CTL's mission and a forward-looking perspective on 6G. Their input provided clear direction on technical priorities, including propagation measurement, AI-native systems, and integrated sensing. It reinforced NIST's critical role in enabling secure, high-performance 6G networks through trusted measurement science and standards leadership.

Following the stakeholder panels, CTL synthesized all internal and external gap inputs into thematic categories that include measurements, datasets, and standards. Internal staff prioritized gaps using a similar matrix to external SMEs, ranking each gap based on urgency, impact, and importance, in addition to CTL's unique ability to address each need. From this prioritized list, roadmap teams crafted three to five draft R&D goals per topic area, each accompanied by a clear problem statement and aligned with measurable outcomes. CTL staff developed these goals collaboratively to ensure technical feasibility and mission alignment.

The roadmap process also included preliminary assessments of resource needs, covering personnel, facilities, and funding required to implement each goal. Teams outlined internal action plans and draft timelines, ensuring the goals could be operationalized effectively. Finally, CTL consolidated all roadmap elements into cohesive drafts. CTL leadership and technical POCs reviewed documents for clarity, feasibility, and strategic alignment, setting the stage for roadmap publication and subsequent implementation across the laboratory's research programs.

Key Trends and Drivers

Various external factors shape the future of 6G Communications, such as industry developments, regulatory fluctuations, and emerging technologies. These trends and drivers, drawn from market research and literature reviews, influence research priorities. Identifying trends and drivers ensures CTL pursues research that accounts for ongoing technological advances, policy and regulatory changes, and activities within the communications market. This step enables CTL to set R&D goals that complement technical trends and research opportunities within the 6G Communications ecosystem. Understanding these drivers supports alignment between research priorities and anticipated technological shifts, helping ensure that the work remains proactively positioned and strategically relevant.

AI-Native, Data-Driven Networks

6G is evolving from "AI-assisted" to fully "AI-native" systems in which machine learning is embedded within primary network functions. The 3rd Generation Partnership Project (3GPP) is looking to expand the Network Data Analytics Function (NWDAF) defined in 5G into a distributed AI engine to provide AI-as-a-Service (AIaaS) through the core and RAN. The literature emphasizes that AI-based solutions require explainability and robustness across the entire ML pipeline, including dataset curation, drift detection, and uncertainty calibration, to be widely adopted. The success of this transformation depends on reproducible benchmarks and trusted datasets, exemplified by initiatives such as the NextG Channel Model Alliance and DeepSense 6G, to support transparent evaluation and safe deployment.

Convergence of Sensing, Communication, and Non-Terrestrial Networks

Integrated sensing and communication (ISAC) capabilities are expected to be a defining feature of 6G, enabling cooperative localization, environmental awareness, and efficient spectrum utilization through shared radar-communications infrastructure. Advances in unified channel modeling and stochastic-geometry-based performance analysis now support more repeatable and comparable evaluations. In parallel, non-terrestrial networks (NTN), codified in 3GPP Releases 17 and 18, are extending coverage and resilience by integrating satellites, high-altitude platforms, and sidelink communications. ISAC and NTN represent a critical convergence of terrestrial and non-terrestrial capabilities that will require standardized measurement methods and interoperable performance metrics.

Higher Data Rates and Energy Efficiency

Higher data rates are expected for 6G systems, perhaps as high as 100 Gbit/s to 1000 Gbit/s. Such high data rates may be achieved through a combination of higher order modulation schemes, higher bandwidth, and use of multiple independent data streams using multiple antennas. The shift into D-band and higher frequencies offers more bandwidth to enable higher symbol rates but introduces significant efficiency and measurement challenges. Recent Complementary Metal-Oxide-Semiconductor (CMOS), Silicon-Germanium (SiGe), and Indium Phosphide (InP) device implementations achieve exceptional data rates but remain constrained in energy efficiency. Higher-order modulation schemes increase the number of bits transmitted for each symbol but are much less tolerant of signal distortion and interference, particularly for wider bandwidths. Multiple antenna techniques pose additional challenges and could be limited by channel conditions and system overhead. When combined with expanded sensing capabilities, the challenges for higher data rate communications are significant and will require new metrology to validate higher performance for materials, devices, components, and antennas.

SiGe power amplifiers, for example, reach only ~2 % Power Added Efficiency (PAE) at 260 GHz. Achieving sustainable performance at these frequencies will require architectural innovations such as hybrid beamforming, arrays-of-sub-arrays, and duty-cycled operation. Progress will depend on the availability of traceable high-frequency metrology, an area where international standards are sparse above 110 GHz.

Secure, Interoperable, and Standardized 6G Ecosystems

The post-quantum era will introduce new cryptographic requirements, with early testing of Transport Layer Security (TLS) 1.3 Post-Quantum Cryptography (PQC) ciphers (e.g., Kyber, Dilithium) demonstrating measurable impacts on latency and throughput in telecom environments. Security frameworks such as “Intelligent Zero-Trust” advocate continuous verification, policy-driven micro-segmentation, and telemetry-rich monitoring for both core networks and multi-vendor RANs. Some research further explores quantum key distribution (QKD) as a complementary resilience measure. At the same time, 6G aims to provide ubiquitous communications, requiring seamless integration of billions of devices with varying capabilities from different vendors. Global interoperability across wireless network deployments is only achievable through harmonized test methods and standardized interface specifications, underscoring the need for shared, scientifically validated measurement frameworks.

6G Communications Technology Gaps

CTL identified roadmap gaps through structured interview sessions with internal 6G Communications SMEs. During interviews, SMEs discussed critical research gaps, assessed existing capabilities, and highlighted opportunities for future innovation in 6G Communications. After several iterations of writing, review, and SME input, the gaps were cleared for external review.

A group of experts in 6G Communications was chosen for their years of experience, level of expertise, prior collaboration with NIST or CTL, and understanding of industry needs. Participants from academic, industry, and government backgrounds reviewed and refined the list of gaps to ensure alignment with evolving technological needs, maximizing the lab’s impact in advancing reliable, resilient, and secure communication systems.

When providing verbal feedback, panel participants commented on which gaps they believed CTL was best positioned to pursue. Through both internal and external interviews, SMEs identified 22 gaps in 6G Communications, which were prioritized based on importance within the industry, level of urgency, and current CTL capabilities. Internal and external SMEs participated in prioritizing gaps to ensure both CTL and industry needs were represented. Once identification and prioritization were complete, the gaps were reviewed by CTL during Strategic Planning Session Three.

After rigorous review during Strategic Planning Session Three, 6G Communications POCs selected 16 top priority gaps that CTL can accomplish within the next five to seven years. The chosen gaps clearly align with 6G Communications Key Trends and Drivers, speaking to the depth and breadth of expertise within internal and external SME groups. These 16 gaps, listed below, were used to develop the R&D goals crafted by CTL to guide research efforts, addressing critical research needs in 6G Communications. Each goal identifies the gaps being addressed, and many gaps are addressed by more than one goal.

Intelligent 6G: propagation modeling, autonomous networking, and data infrastructure

AI/ML-Based Propagation Models and Radio Frequency (RF) Propagation Datasets

Traditional propagation models, such as those defined by 3GPP, are stochastic models based on fixed environments. These models typically describe the average behavior of signals in different environments, such as rural or urban areas, and include corrective factors for varying frequencies. However, to optimize spectrum usage, it is crucial to account for the dynamic aspects of these environments and adjust them in real-time. This is particularly important for high frequencies, such as mmWave and Sub-THz, where even small changes like the movement of tree leaves or other objects can significantly affect signal propagation. New propagation models that capture these subtle but impactful environmental changes are needed to develop high-performing RF systems capable of resolving individual signals. Also, datasets are needed to validate and refine physics-based models and to develop digital twins of the environment. As with all AI and machine learning challenges, large datasets are currently unavailable and are essential for training, validating, and comparing these new models.

CTL will continue to lead and contribute to the NextG Channel Model Alliance (nextg.nist.gov) to promote collaboration between industry and academia. This effort will focus on collecting and distributing curated datasets that can be used to develop innovative AI/ML-based channel models and refining theoretical and physics-based models. Additionally, CTL will work on developing new measurement and modeling techniques to address the resolution requirements and the associated data size challenges.

AI for Networking

AI will enable autonomous and intent-based operation of the 6G network by including closed-loop orchestration, self-optimization, service lifecycle management, and predictive maintenance of the network infrastructure. AI will be responsible for making real-time decisions across distributed network functions, managing network slices, and adapting resources to meet user intents and service-level objectives. To achieve this, several key challenges must be addressed, including developing semantic models to interpret and translate high-level intents into network actions and mechanisms to perform continuous monitoring and autonomous policy enforcement. There is a need to define a standard format for the data exchanged between the network functions (NFs) and common APIs to access the data and control the NFs that would ensure interoperability across different vendors. Additionally, the availability and quality of data present ongoing challenges, as effective automation relies on comprehensive, labeled datasets to train models, which are often proprietary or confined to specific organizations.

CTL will support the adoption of AI-based orchestration systems by working with Standards Development Organizations (SDOs) to standardize frameworks enabling continuous monitoring and orchestration. CTL will also develop open-source testbeds to demonstrate the feasibility of autonomous orchestration.

AI Native Architecture

The idea that every part of the network will leverage AI/ML algorithms for configuration and optimization means that data will be extracted and transported across the network for training, inference, and control. Research is needed on how to best manage this information, including the creation of a new “data” plane that would supplement the existing control and user planes. Additionally, there is a need to define AI-native network functions capable of handling AI workflows, including distributed or federated frameworks.

CTL will develop guidelines on how to instrument the various components of the network to generate data that will be used as input to the AI/ML algorithms and digital twins.

Integrated Sensing and Communication (ISAC)

Channel Models for Sensing Applications

Channel models developed for network communications need to be updated to incorporate the characteristics and key performance indicators of various types of sensing systems, such as radar. Researchers need to validate the channel models used in wireless network research and design, capture the right characteristics relevant to sensing, and further refine those models. Algorithms supporting 6G signal transfers will need to assume a certain channel model, and there are ongoing activities in 3GPP to decide whether these channel models will describe communications, radio, or joint sensing signal behavior. There is a need to define whether bandwidth requirements for communications applications are sufficient to support radar sensing use cases and whether joint communications environments will need to leverage two-channel models to characterize communications and radar propagation simultaneously.

CTL will continue to work with SDOs to standardize new channel models suitable for sensing applications. Contributions will focus on providing methodologies for collected measurements and parameter values for various use cases based on measurements collected using calibrated channel sounders.

New Measurements for Target Sensing

As 6G evolves to include integrated sensing functions, wireless systems will need to detect, track, and characterize targets in highly diverse environments, including crowded indoor spaces, urban canyons, and high-speed vehicular scenarios. Standards bodies such as 3GPP, Institute of Electrical and Electronics Engineers (IEEE), and International Telecommunication Union (ITU) are defining new ISAC use cases involving mobility, human interaction, and dynamic objects, all of which require precise sensing capabilities beyond what today’s communication systems can provide. However, the measurement science underpinning these new use cases remains underdeveloped. Current test methods are not designed to quantify sensing performance over communication waveforms or to capture the subtle effects of interference, mobility, and multipath. Moreover, there are no widely accepted performance metrics or standardized environments for evaluating sensing resolution, accuracy, refresh rate, or reliability across different frequency bands and deployment topologies. These gaps are particularly limiting in scenarios involving partial target illumination, non-line-of-sight conditions, or rapidly changing clutter environments.

CTL will develop validated sensing performance metrics, establish test procedures for radar-like functions over communication waveforms, and contribute reference data and calibration techniques for use in standards bodies. This will support objective evaluations across diverse deployment scenarios and promote consistency across international efforts.

Tools to Evaluate Performance of ISAC Configurations

Robust modeling and simulation tools are critical to evaluate and optimize ISAC systems, yet most existing tools focus exclusively on either communication or sensing. As a result, engineers lack the ability to assess trade-offs between throughput, latency, and sensing accuracy in an integrated fashion, especially when designing systems for dynamic environments. Link-level and system-level modeling tools need to account for unique features of ISAC, including shared waveform design, joint beamforming, and sensing-induced interference. Additionally, tools must support both far-field and near-field applications where partial target illumination and reactive environments introduce complex effects not captured by current models. Computational load, signal fusion methods, and the impact of mobility must also be accurately represented. Without validated tools, researchers cannot test new ideas at scale, and industry cannot make informed design choices. Large-scale testing in the physical world is expensive and often infeasible at early development stages, underscoring the need for trustworthy digital twins and simulation environments. However, as research progresses, testbed capabilities must also be developed to demonstrate ISAC capabilities and validate the sensing performance.

CTL will develop and validate open-source or reference modeling platforms that simulate ISAC configurations under real-world propagation and hardware constraints. These tools, complemented by testbed demonstration, would enable industry and researchers to compare architectures, optimize system tradeoffs, and validate design choices prior to deployment.

Improved Indoor Localization

Indoor localization, or “positioning” in 3GPP terminology, is a promising and critical application of ISAC in 6G. The fusion of sensing and communication functions allows wireless systems to use reflected signals not only to communicate with users but also to infer their position and orientation with higher precision. ISAC enables localization methods that go beyond conventional signal strength or time-of-arrival metrics—leveraging angle-of-arrival (AoA), Doppler shifts, and channel impulse responses derived from joint radar-communication waveforms. This fusion is particularly important in complex indoor environments where GPS is unavailable and where clutter, multipath, and mobility complicate traditional localization techniques. However, technical challenges remain. ISAC-based localization requires fine-grained channel estimation, synchronization across multiple antennas and nodes, and high-fidelity channel models that capture both communication and sensing dynamics. Integrating localization into the network stack requires new approaches for control signaling, timing alignment, and context-aware beamforming. Moreover, current testing environments and evaluation methods are not designed to validate positioning performance under these joint modalities.

CTL will establish indoor localization test environments with traceable ground truth, creating evaluation methodologies for multipath-rich environments, and contributing to positioning standards. CTL will lead measurement campaigns and develop traceable positioning metrics that inform both commercial solutions and public safety systems.

Combining CSI and Sensing Information to Optimize Network Performance

Channel state information (CSI) provides rich data on the propagation environment, but it is typically used only for optimizing communication parameters. Meanwhile, ISAC introduces the potential to obtain complementary sensing data such as object range, velocity, and angle from reflected signals. Combining CSI and sensing-derived data streams could offer a more holistic understanding of the environment, enabling more efficient beamforming, adaptive modulation, and predictive handovers. However, the methods for integrating these data sources remain underdeveloped. There is no standard approach for synchronizing and calibrating CSI with external or passive sensing information, and the algorithms required to fuse this data in real time are computationally demanding. Moreover, performance metrics that quantify the benefits of CSI-sensing fusion are not well defined, making it difficult to evaluate trade-offs or validate improvements. Current systems are often designed with rigid signal processing chains that cannot flexibly combine multiple sources of environmental knowledge. Research and testing are needed to understand how to fuse these signals effectively and use them to improve overall network performance.

CTL will develop measurement methods and testbeds to evaluate CSI-sensing fusion, providing calibration guidance, and creating benchmarks for how fused data can improve the network performance.

ISAC for Public Safety Communications

Public safety operations often occur in unpredictable, degraded, or high-risk environments, such as flooded buildings, burning structures, and collapsed tunnels, where situational awareness and robust connectivity are equally vital. ISAC has the potential to transform public safety communications by providing real-time environmental sensing integrated directly into the wireless communication infrastructure. First responders could benefit from ISAC-enabled networks that detect obstacles, track personnel, and identify hazards using the same waveforms used for voice and data transmission. However, realizing this potential requires integrating ISAC functions into public safety network architectures and protocols. The system must be able to prioritize sensing requests (e.g., detecting movement behind walls) alongside critical voice/video traffic. It must manage limited bandwidth, power, and processing resources under stressful and dynamic conditions. Furthermore, specialized interfaces and APIs may be needed to allow ISAC data to feed into command centers or augmented reality displays. Public safety also raises the level of data security, latency guarantees, and system resilience requirements that must be addressed for ISAC to be trusted in the field.

CTL will support the integration of ISAC and public safety communications by developing joint test procedures, validating performance in emergency-like scenarios, and contributing technical expertise to standards bodies focused on public safety.

Space-Air-Ground Convergence for 6G

Non-Terrestrial Channel Models

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

CTL will work with its stakeholders to conduct measurements for Non-Terrestrial Networks (NTN) or use measurements to develop new channel models as part of its future Space Communication portfolio.

Sidelink

Enabling communication directly between end-user devices or through other end-user devices remains a key ingredient in providing ubiquitous coverage. During an emergency situation or in remote locations where traditional infrastructure may not be available, enabling direct communication between devices becomes critical. With sidelink as the underlying technology, developing device-to-device (D2D) protocols that are reliable, low-latency, and capable of prioritizing mission-critical traffic will ensure seamless communication during mission-critical operations. Sidelink is also the base protocol for other services such as vehicular communications (V2X) and Aircraft-to-Anything (A2X). There are technical challenges that need to be resolved in terms of performance and backward compatibility since a lot of those devices, like those embedded in cars, have a much longer life cycle than regular handsets. Therefore, enabling NR sidelink devices to operate in 6G requires further research.

CTL will contribute by researching and testing D2D communication protocols specifically for mission-critical communications, including public safety and military use cases, ensuring they function reliably in challenging environments (like areas with no network coverage). This will involve performance measurement to inform standards and improve critical communication effectiveness.

NTN/TN Integration

Satellites and airborne platforms are increasingly relied upon in areas where terrestrial communications are not available (e.g., in remote areas or during disasters where terrestrial equipment is impacted). Reducing Round Trip Time (RTT) between ground devices and these systems is crucial for reducing delays, improving responsiveness, and enhancing the quality of experience, especially in public safety communications. The integration of TN and NTN is not trivial because there are different architectures based on the altitude of the satellites, each providing different coverage, latency, and throughput characteristics while also experiencing different operational factors, such as satellite co-existence, differing beam footprints, and geo-location. NTN also encompasses devices such as drones and balloons. Provisioning and monitoring end-to-end services across those heterogeneous access technologies must still be defined for 6G.

CTL will work with Industry and standards bodies (e.g., 3GPP, Internet Engineering Task Force (IETF)) to refine or define measurement methods for these new hybrid networks. CTL will also have an impact by developing testbeds to analyze select use cases for NTNs. These testbeds will measure performance, demonstrate and refine communication protocols, and ultimately inform standards development for reliable, low-latency communication in challenging environments.

Security and Resilience

Zero Trust Architecture

Initial efforts to incorporate the principles of zero trust (ZT) security into the 5G core (in 3GPP) and RAN (in the O-RAN Alliance) have resulted in some progress in current 5G security standards, but the effort is far from complete as viewed by common ZT maturity models. Most of the work to date has focused strictly on communications security, conducting gap analyses, and documenting existing communication security controls. To achieve a fully mature ZT architecture, 6G standards development will have to broaden its scope to address providing protection for all of 6G's communication channels, protection for new network functions and micro-services, and protection for the data in transit, in use, and at rest. This increased focus on data protection, including authorization and access control, must address both user data and data generated within the network and extend to users/applications outside the 6G network. A mature 6G ZT architecture will also require the integration of dynamic policy management and enforcement informed by continuous monitoring, cyber hygiene analysis, behavioral analytics, threat intelligence, and identity/access management.

6G standards will further embrace disaggregated cloud-native architectures, requiring the granularity of ZT security controls to evolve from aggregate channels/interfaces between major network architectural elements to session-level security among communicating network functions and micro-services. ZT security, in this context, will require identity and access management for micro-service workloads, APIs, and network exposure functions. Potential new 6G in-network technologies, such as network-embedded AI-native functions, will require analysis of new threat vectors, risk scenarios, and mitigation techniques.

NIST will increase its research efforts to design, test, and standardize ZT security mechanisms to adequately protect 6G networks, applications, and users, addressing the range of new technologies, services, and use cases planned for 6G. This will leverage NIST's leadership role in developing ZT security architecture and AI/ML risk management techniques for 5G RAN standards.

Quantum-Safe Networks

The growing threat of the development of cryptographically relevant quantum computers (CRQCs) within the decade requires that 6G security standards use quantum-resistant algorithms from the start. For some types of highly sensitive data, the potential to collect traffic today and decrypt it later means the threat quantum computing poses to the cryptography used throughout mobile network infrastructure and device standards already exists. As CRQCs emerge, new threats to existing mobile network control and management channels will expand the risks to include potential disruption or subversion of live network operations.

While the threat of CRQCs is real, not all common forms of cryptography are vulnerable to known quantum algorithms. CRQCs pose significant threats to the asymmetric algorithms used in public key cryptography. These are the algorithms typically used in key management and authentication services. Symmetric cryptographic algorithms, commonly used with shared session keys for bulk data encryption, are not vulnerable to known quantum algorithms when using large keys. Of course, if one breaks the algorithms used for key establishment, then decrypting the session data encrypted using those keys becomes trivial.

Quantum-vulnerable asymmetric algorithms are used extensively throughout 5G standards in key agreement protocols for TLS and IPsec channel security, OAuth and X.509 authentication protocols, 802.1X network access control, Subscription Concealed Identifier (SUCI) privacy controls, digitally signed software modules, etc. NIST has published the first set of standards for quantum-resistant cryptographic protocols to address these vulnerabilities, but much work needs to be done before they can be readily incorporated into 6G standards.

Ensuring that 6G security is quantum-safe from the start will require significant effort to expedite the standardization of post-quantum and hybrid algorithms in many different security protocols and technologies. In most cases, the security protocols used in mobile networks are standardized in other SDOs, including the IETF, IEEE, and European Telecommunications Standards Institute (ETSI). Work to incorporate the new NIST-published post-quantum algorithms in these protocols is underway. In most cases, protocol standards that were designed to be agile with respect to cryptography can be extended to add quantum-resistant algorithms.

While work is progressing to define quantum-resistant cryptography and to incorporate the resulting algorithms into existing security protocol standards, much work remains to define a comprehensive strategy to incorporate these technologies into 6G standards. To some extent, the threat space (i.e., quantum computing), mitigation techniques (i.e., quantum-resistant cryptography), and application space (i.e., 6G standards) will evolve simultaneously. Confidence in cryptographic algorithms increases with time. Given the relatively recent standardization of quantum-resistant algorithms, 3GPP will most likely adopt hybrid or layered security mechanisms that combine current security technologies with new quantum-resistant techniques.

Significant research will be needed to understand and verify the security properties of 6G security architectures that incorporate such hybrid techniques, to characterize the performance implications of new security protocols and algorithms across a broad scope of 6G protocols, functions, and use cases, and to develop appropriate deployment guidance for their use in real 6G networks.

NIST will work with industry and relevant SDOs to expedite the development of quantum-safe 6G network standards, evaluate their performance and behavior, and provide guidance for their adoption in mission-critical networks.

High-Speed 6G Readiness: Models, Antennas, and Materials

Metrology to Characterize Wideband Distortion

Measurements of highly modulated signals over wide bandwidths, both at microwave and sub-THz frequencies, demand high accuracy and precise uncertainty quantification in both frequency and time domains. Current on-wafer and over-the-air metrology systems are not adequate for such demanding measurements due to the distortion created by the measurement systems themselves, and the need for consistent calibrations across frequency and time domain approaches. In addition, devices operating at higher speeds can generate heat that can affect the measurements and need to be compensated for accurate characterization.

CTL will leverage its expertise to develop new probe-based and over-the-air distortion measurements, push traceable measurements to higher operating frequencies, and incorporate high-frequency harmonic and nonlinear effects into new broadband distortion models.

New Antenna Architecture for Massive Multiple Input/Multiple Output (MIMO) Antennas

6G operations at mm-Wave, sub-THz, or THz frequencies face significant challenges caused by the large path loss and signal attenuation due to the atmosphere and blockage, requiring antennas with high gain and high directionality. Current designs are not suitable for these conditions and are not scalable to the hundreds or even thousands of antenna elements that are needed, whether it is about performance, energy efficiency, or cost due to the need for many individual RF chains. Furthermore, 6G will require 3D coverage to support NTN communications that conventional planar arrays cannot provide. Therefore, new architectures and antenna designs are necessary to support new geometries that enable beamforming in all directions.

CTL will develop new measurement techniques to evaluate the performance of new multi-antenna architectures.

Improved Directionality Control

There is a continuous demand for improving the speed and accuracy of the directionality of large and multi-element antennas. This need is particularly pressing when it comes to controlling single directions at a time, due to the blockage challenges associated with the short wavelengths found at higher frequencies and support for NTN communications. This can involve the development of new beamforming techniques or analog front-end technologies. However, while communication waveforms only need directional beam patterns to support a reliable connection, radar devices will scan over the whole angular range. Therefore, instead of accurate beams, radar beam patterns spread across a wide area and use an immense amount of power. The support for ISAC brings additional constraints that must be accounted for in the beam management solutions.

CTL will develop new algorithms, including AI-based solutions, to improve the performance of beam management in mmWave and sub-THz frequencies.

Traceable Measurements for High-Bandwidth Materials and Circuits

Key material properties such as complex permittivity, loss tangent, and conductivity must be measured with high accuracy and traceability across wide frequency ranges, up to 350 GHz or more. Higher-frequency measurements are key to understanding the nonlinear distortion created by 6G materials and components, enabling unprecedented control of signals at the carrier and multiple higher-order harmonic frequencies. Today, industry lacks standardized, International

System of Units (SI)-traceable methods for these measurements, especially for emerging materials used in high-frequency packaging and circuit integration. In-plane and out-of-plane permittivity measurement methods are underdeveloped, limiting the understanding of anisotropic material behavior critical to multilayer and flexible substrates. Current commercial tools and methods are often inconsistent, lacking agreement across vendors. Moreover, accurate material and circuit component models that feed into simulation and design tools are limited by a lack of reliable data. Without traceable measurements, circuit designers face uncertainties that lead to design margins, increased cost, and reduced performance undermining 6G system goals.

CTL will invest in developing SI-traceable measurement standards and methodologies for high-frequency materials and circuits. New methods will be developed for in-plane and out-of-plane permittivity, enabling full 3D characterization of materials. CTL expertise will also enable new on-wafer calibration services for mm-wave and sub-THz frequencies.

Research Goals and Implementation Pathways

Research Goals and their added context Supporting Gaps, Action Items, and Resource Requirements provide a structured link between CTL strategic objectives and specific technical challenges. Each roadmap defines three to five research goals that explicitly target prioritized R&D gaps, identified from stakeholder engagement and internal analysis. Action items, such as developing new methods, tools, or collaborations, support the research goals, which are strategically designed to produce measurable outcomes.

CTL enables the successful execution of resource goals by outlining resource requirements, including personnel, facilities, and funding. Each goal also includes anticipated standards contributions, such as participation in SDOs, submission of metrology protocols, and/or dataset dissemination. Success measures track progress toward goal completion, including technical milestones, peer-reviewed outputs, standards adoption, and stakeholder engagement. This structure focuses investments made by CTL and drives high-impact, standards-relevant results aligned with national priorities and internal capacity.

Goal 1: Enable AI-Native 6G Applications

Develop high-quality datasets through curation and publication to help train, baseline, and benchmark new AI applications.

Why is this a Priority?

Transitioning from AI-augmented to AI-native 6G networks calls for the smooth insertion of AI across all operational planes, from the physical layer handling signal transmission and reception, to the service management and orchestration, in which AI powers autonomous decision-making, predictive maintenance, and intent-based service management. Realization of this vision hinges on networks well instrumented with devices that provide trusted, standardized data. In the absence of standardized data and interfaces, advances toward AI-native capability would be hindered, interoperability would be limited, and innovations would be limited to siloed, proprietary domains.

AI-native networks also require high-quality publicly shared datasets about the performance and behavior of wireless networks, from propagation to application, to train, baseline, and benchmark new AI models. The lack of datasets hinder the construction of sophisticated AI/ML-based models that adapt in real time to environmental changes and that create high-fidelity digital twins.

Why NIST?

CTL is uniquely positioned to address these gaps through its nonpartisan, measurement science-informed leadership and its convening power across industry, research, and government. CTL's leadership of the NextG Channel Model Alliance enables an interoperable infrastructure for acquiring and distributing curated datasets to support AI/ML-based channel modeling and calibration of theoretical and physics-based models.

NIST's experience in crafting traceable measurement methods guarantees that the datasets provide resolution, accuracy, and repeatability properties needed to train robust AI models. Its efforts in describing a new "data plane" and AI-native network functions are complementary to the need for interoperable frameworks and open APIs that support cross-vendor orchestration and standard AI workflows.

With open-source testbeds, measurement guidelines, and contributions to SDOs, NIST can help assure that AI-native 6G architectures are based on reproducible science, globally compatible across networks, and secure for mission applications.

Implementation Pathways

The table below links each 6G Communications research goal to the gaps it addresses, key action items, required resources, standards contributions, and success measures. Together, these elements provide a clear path from strategic objectives to measurable outcomes.

Supporting Gaps	• AI/ML-Based Propagation Models and Radio Frequency (RF) Propagation Datasets

	• AI for Networking • AI Native Architecture
Action Items	• Survey existing repositories (internal and external such as https://ieee-dataport.org/datasets) and identify gaps • Define the Top 5 categories for the data CTL would provide (e.g., propagation, sensing, spectrum usage, public safety user data) • Define use cases/verticals for each category of data relevant to CTL research (e.g., propagation for public safety, sensing for industry) • Develop measurement capabilities and processes to collect and label data • Conduct measurement campaigns • Develop recommendations on how to use CTL data
Resources Requirements	• Funding • Specialized staff who understand emerging AI architectures • Clear taxonomy/process for labeling metadata assigned to each dataset. • Dynamic, scalable platform for sharing datasets supporting the full scope of AI use cases (i.e., NextG Channel Model Alliance for RF Propagation Data)
Standards Contribution	• 3GPP: Incorporate AI models for propagation, interference, and sensing into specifications • Standardized performance benchmarks for mission-critical networks • Support relevant standardization efforts in IEEE, and ITU-R, such as definition of Key Performance Indicators (KPIs) for AI native solutions
Success Measures (KPIs)	• Dissemination of datasets through online platform. • Publication of NIST guidelines for developing curated datasets for AI. • Demonstrated use of CTL's datasets by SDOs, industry, government, or academia

Goal 2: Enable Sensing

Integrate sensing and communications systems in 6G for use by the U.S. government in public safety and mission-critical applications.

Why is this a Priority?

ISAC capabilities are emerging as a defining feature of 6G, enabling networks to provide both high-performance connectivity and advanced situational awareness. For U.S. Government, defense, and public safety agencies, this integration is critical: ISAC can enhance mission success in complex environments such as urban canyons, crowded indoor spaces, disaster zones, and high-speed mobility scenarios.

Nonetheless, the tools, methods, and models to fully develop and integrate with communications systems is lacking. Consensus test methods and performance measures that accurately quantify sensing capabilities across communication waveforms do not exist, especially in an environment of interference, mobility, multipath, and rapidly changing clutter. Validated models, simulation platforms, and benchmarks to help determine sensing range and accuracy, network throughput, and latency trade-offs do not exist, either, which hinders standards alignment and impedes innovation.

By filling these gaps, ISAC will be ready to facilitate an array of mission-critical use cases, from fused channel state information (CSI) and sensing data for adaptive network optimization, to ISAC-powered public safety systems that can detect danger, track personnel, and inform real-time decision-making. Standardized, validated sensing functionality will be key to reaching interoperability, reliability, and trustworthiness across vendors and deployment scenarios.

Why NIST?

CTL is best suited to drive ISAC measurement science and standards development through its central role, technical capability, and close collaborations with industry, academia, and government agencies. CTL's efforts span across the complete ISAC technology chain:

Metrics and Calibration – Establishing verified sensing performance measures, designing calibration tools, and defining test procedures for radar-like capabilities across communication waveforms.

Modeling and Simulation – Building open-source or reference ISAC modeling environments that incorporate communications and sensing behaviors, which allow system designers to test, compare, and optimize architectures before deployment.

Data Fusion – Methodologies and benchmarks for integrating CSI with sensing-acquired data for better beamforming, predictive handovers, and network performance.

Public Safety Integration – Testing and designing ISAC capability in emergency-like conditions, contributing to standards bodies for public safety, and ensuring that ISAC conforms to the high security, low latency, and resilience needs of mission-critical communications.

By offering traceable measurement techniques, common test environments, and publicly accessible data, NIST can stimulate ISAC innovation, provide for technical interoperability, and facilitate its widespread adoption in both commercial and government networks.

Implementation Pathways

The table below links each 6G Communications research goal to the gaps it addresses, key action items, required resources, standards contributions, and success measures. Together, these elements provide a clear path from strategic objectives to measurable outcomes.

Supporting Gaps	• Channel Models for Sensing Applications • New Measurements for Target Sensing • Tools to Evaluate Performance of ISAC Configurations • Improved Indoor Localization • Combining CSI and Sensing Information to Optimize Network Performance • ISAC for Public Safety Communications
Action Items	• Document sensing requirements for different user groups and scenarios (e.g., public safety, industrial automation, functional safety) • Identify and develop CSI, protocol, and spectrum sensing measurements and metrics needed to support sensing in mission critical applications • Collect sensing measurements • Advance sensing standards • Identify and leverage existing Testing Facilities capable of conducting measurements and evaluating radar systems
Resource Requirements	• Funding from peer government agencies that will benefit from data / standards / sensing advancements (DOD, DHS) • Define a more specific value proposition for how CTL sensing advancements impact commercial industry (in addition to government partners) • Integrated capability of a 6G network implementation with a radar-like sensing capability for in-lab use • Instruments for conducting sensing measurements • Staff capable of conducting measurements • Expertise in signal processing
Standards Contribution	• 3GPP: Provide data and models to relevant working groups. Also contribute to architecture and protocol specifications • ITU-R and IEEE wireless standards to include sensing and performance assessment • ATIS NextG Alliance
Success Measures (KPIs)	• Inclusion of CTL measurements and models in standards specifications • Demonstration of sensing in select applications • Establishment of OA funding sources

Goal 3: Make 6G Systems more robust and resilient

Make 6G systems viable for the United States Government, public safety, and other mission-critical applications.

Why This Is a Priority?

For 6G to be trusted in U.S. Government, public safety, and other mission-critical operations, it must maintain robust, low-latency connectivity even in degraded or infrastructure-limited environments. Achieving this requires resilient architectures that integrate TNs with NTNs, as well as enabling reliable D2D communications through sidelink.

In disasters, remote communications, and defense applications, NTN, consisting of satellites, high-altitude platforms, drones, and balloons, offers much-needed coverage when ground systems are unavailable or out of commission. Yet, combining TN and NTN poses several challenging issues: different orbital altitudes create different latency, throughput, and coverage behaviors; beam shapes and geolocation differ; and co-existence of TN/NTN with additional spaceborne entities needs to be addressed. Unless hybrid end-to-end service provisions and monitoring models become standard, performance variability and lack of interoperability would result.

Sidelink functionality, which provides for direct device-to-device communication without the need for network infrastructure, is just as essential for mission continuance during emergency scenarios. Sidelink provides an underlying foundation for public safety communications, V2X, and A2X scenarios. However, sidelink also experiences both technical and adoption hurdles, including limited range and backward compatibility requirements for devices with deep lifecycles and ensuring high mobility/congested environments provide predictable performance. Unless sidelink performance improves with the introduction of multi-hop features and support in 6G, sidelink becomes an underutilized capability, exposing mission-critical networks to coverage holes.

Why NIST?

CTL is especially well-suited to this challenge of enhancing robustness and resilience through advancing measurement science, testbeds, and standardization inputs needed for reliable hybrid and infrastructure-free communications.

TN/NTN Integration – CTL shall cooperate with standards organizations like 3GPP and IETF in specifying measurement approaches for hybrid network performance, taking into account latency, coverage, and coexistence parameters. Testbeds shall be constructed for testing real-world NTN scenarios, verification of communication protocols, and guiding standards for low-latency, high-reliability performance in hostile or austere environments.

Sidelink Performance for Mission-Critical Applications – CTL will research and test D2D protocols optimized for public safety, measuring performance under infrastructure-free and degraded conditions. This work will produce reference data and benchmarks to guide protocol improvements and ensure sidelink can support time-critical, priority traffic.

By integrating its non-partisan stance with extensive technical expertise, NIST can close gaps between public safety needs and leading-edge commercial development, so that 6G systems are both technically advanced and operationally robust in even the most demanding scenarios.

Implementation Pathways

The table below links each 6G Communications research goal to the gaps it addresses, key action items, required resources, standards contributions, and success measures. Together, these elements provide a clear path from strategic objectives to measurable outcomes.

Supporting Gaps	• Non-Terrestrial Channel Models • Sidelink • NTN/TN Integration
Action Items	• Investigate sidelink research opportunities, given that very few industry / academic organizations are focused there • Define government or mission-critical requirements for NTN / TN system integration • Identify and address gaps in mission-critical wireless networks to satisfy reliability, latency, and resilience requirements • Develop methodologies for detecting behavior deviations within the wireless channel or metrics produced by the communications protocol
Resource Requirements	• Additional staff with standards expertise to engage with 3GPP more substantively • Controllable laboratory test environments supporting TN and NTN • Scalable traffic generation tools like high-capacity traffic emulators • Advanced real-time measurement and monitoring systems • More specific 3GPP engagement focused on sidelink research • Optimize management of resources required for NTN / satellite measurement (CTL currently lacks the resources necessary to launch satellites and weather balloons). Establish partnerships with NTN providers

Standards Contribution	• Advocate sidelink to 6G framework and adaptation of 5G sidelink to 6G with no or minimal modifications • Incorporate government or mission-critical requirements on NTN into 3GPP standardizations • Standardize NTN technology so that it provides robust and resilient connectivity • Incorporate performance test methodologies and scenario-specific environments into applicable standards such as IEEE 3388
Success Measures (KPIs)	• Publication of NIST sidelink and NTN technology performance evaluations in conferences or journals • Contributions to 3GPP integrated in standards specifications • Adoption of simulation tools developed by NIST for sidelink and NTN by the research community

Goal 4: Make 6G Infrastructure Secure

Make 6G infrastructure secure for the United States Government, public safety, and other mission-critical applications.

Why This Is a Priority?

6G network security is expected to adopt and build upon many of the security and resilience techniques initiated in 3GPP and O-RAN 5G standards but will require significant enhancements to address new use cases and technologies unique to 6G. The introduction of technologies such as AI-native network functions and integrated sensing into 6G networks will require new threat analyses and new approaches to securing both the new capabilities and their potential interactions with existing network functions and services. New proposed 6G use cases, such as immersive communication and zero-energy devices, will pose challenges to existing security mechanisms for preserving confidentiality, integrity, privacy, and resilience. New use cases that tightly integrate 6G communications with cyber-physical systems will couple new physical safety requirements to those of network security, resilience, and performance.

While 6G standards may bring significant changes to the technologies and services provided within mobile wireless networks, there will also be significant changes in the external ecosystem in which these networks are deployed and operated. New network implementation architectures and technologies introduce new threats. The continued evolution toward disaggregated cloud-native architectures will significantly influence 6G security requirements and controls. In many cases, key communication functions and security controls of the network will be provided by the underlying implementation environments (potentially outside the scope of 6G standardization). The evolution toward user-centric programmable networks will require exposing more network interfaces and data to external applications. Threats from unwanted emergent network behaviors caused by control logic external to the network will require new approaches to preserving resilience within 6G networks. Finally, region-specific requirements related to security and privacy will require flexibility in 6G communication and data security standards.

Many of the security gaps for 6G remain to be defined as they are highly dependent upon the specific new use cases and technologies that emerge in 6G standards. It is clear in today's threat environment that no new 6G technology or service can be commercially viable unless it can be operated in a secure and resilient manner.

Why NIST?

NIST is well-positioned to provide leadership in advancing ZT and quantum-safe security for 6G because of its extensive experience in cybersecurity standards, cryptographic science, and AI/ML risk management.

NIST is a global leader in defining ZT principles, publishing widely adopted frameworks, and applying these to cloud-native, microservice-based, and AI-integrated systems. This experience positions NIST to extend ZT to the granular, session-level controls required for 6G's disaggregated architectures. NIST's neutral role and technical rigor enable it to develop, test, and standardize identity and access management protocols for microservices, APIs, and in-network AI workloads ensuring robust protection across data in transit, at rest, and in use.

NIST is the ultimate source for standards related to PQC, as it was the first agency to publish a set of quantum-resistant algorithms and spearheads their deployment in several industry segments. NIST's dual capability of being a standards body for cryptography and an independent assessor positions it to coordinate with SDOs (e.g., IETF, IEEE, ETSI) in incorporating these algorithms within 6G protocols that interoperate effectively and perform optimally. NIST's measurement science expertise is key to describing security attributes, latency, and throughput effects of post-quantum and hybrid security mechanisms within mission environments and issuing the necessary guidance for their use within operational 6G networks.

By combining leadership in cybersecurity frameworks, cryptographic standardization, and rigorous performance evaluation, NIST can ensure that 6G security architectures are both zero-trust by design and quantum-safe from inception, meeting the needs of government, public safety, and commercial stakeholders worldwide.

Implementation Pathways

The table below links each 6G Communications research goal to the gaps it addresses, key action items, required resources, standards contributions, and success measures. Together, these elements provide a clear path from strategic objectives to measurable outcomes.

Supporting Gaps	• ZT Architecture • Quantum-safe networks
Action Items	• Evaluate NIST Information Technology Laboratory (ITL)'s capabilities relevant to this goal • Engage with O-RAN Alliance to advance CTL's security research priorities • Define security skill sets that CTL wants to prioritize when advocating for additional funding and staff • Need to use a "whole of NIST" approach to advance these goals
Resource Requirements	• Clear, vetted user requirements for security / accessibility • Expertise in security issues and engage with cybersecurity standards.
Standards Contribution	• Participate in 3GPP and O-RAN Alliance security working groups
Success Measures (KPIs)	• NIST approved PQC algorithms are incorporated in 6G standards • Demonstration of ZT deployment in 6G networks

Goal 5: Validate Performance of 6G Hardware

Advance measurement science to characterize high-speed, high data-rate materials and components.

Why This Is a Priority?

While Mobile Network Operators (MNOs) are currently focused on the mid-band (e.g., 7 GHz-24 GHz), 6G evolution will drive wireless infrastructure into novel performance domains in operation at mmWave, sub-THz, and even THz frequencies, where current device, material, and system architectures have considerable technical difficulties. High-frequency systems need to provide advanced performance, including high directionality, enhanced linearity, high gain, and high efficiency, accommodating both NTN and TN communications, integrated sensing, and large MIMO arrays with hundreds to thousands of antenna elements.

Optimized beam management is key to dealing with blockage, atmosphere-induced attenuation, and mobility issues with short-wavelength operation. ISAC applications add further complications, necessitating beam solutions that can concurrently optimize communications and sensing performance without excessive interference or power consumption. In kind, precise and traceable characterization of high-frequency material properties like complex permittivity, loss tangent, and conductivity is needed for robust design of antennas, packaging, and circuits, at fundamental and higher harmonic frequencies. Current commercial characterization practices do not provide consistent results, causing design uncertainty, increased cost, increased distortion, and fewer performance margins.

Operating above 100 GHz also presents calibration challenges for on-wafer and over-the-air testing, where existing probes, fixtures, and reference standards do not maintain accuracy under high-frequency, high-heat operating conditions. Without robust calibration and measurement science, system performance, including linearity and distortion quantification, will have high uncertainty and be difficult to validate. Addressing these challenges is vital to the development and validation of cost-effective, linear, and energy-efficient 6G hardware.

Why NIST?

CTL is specifically well-positioned to drive the measurement science required to design, test, and validate 6G hardware performance by leveraging traceable measurements and calibrations.

Beam Management Innovation – Leveraging its expertise in wireless metrology and AI-driven algorithm development, CTL can create and validate beam management techniques optimized for both communications and sensing at mmWave and sub-THz frequencies.

SI-Traceable Material Characterization – NIST, as the U.S. National Metrology Institute (NMI), can develop SI-traceable methods of in-plane and out-of-plane permittivity, loss tangent, and conductivity up to and beyond 350 GHz, that would allow industry access to stable, vendor-neutral material data for simulation and design.

mm-Wave and Sub-THz Calibration Services – CTL can create new probes, fixtures, and calibration services to accommodate contact resistance, transmission losses, and thermal issues within mm-wave and sub-THz frequencies, enabling accurate characterization of high-frequency, high bandwidth devices.

Antenna Architecture Testing – With its advanced facilities, NIST can develop measurement techniques to evaluate next-generation massive MIMO and 3D beamforming antenna architectures, producing validated performance data to inform both system design and standards.

By combining traceable measurements, advanced calibration methods, and specialized testing of emerging architectures, NIST can reduce design uncertainty, accelerate hardware innovation, and ensure that 6G systems meet performance, cost, linearity, and energy-efficiency targets for both commercial and mission-critical applications.

Implementation Pathways

The table below links each 6G Communications research goal to the gaps it addresses, key action items, required resources, standards contributions, and success measures. Together, these elements provide a clear path from strategic objectives to measurable outcomes.

Supporting Gaps	• Metrology to characterize wideband distortion

	• New antenna architecture for Massive Multiple Input/Multiple Output (MIMO) Antennas • Improved directionality control • Traceable measurements for high-bandwidth materials and circuits
Action Items	• Develop SI-traceable methods and calibration services for devices and materials from Direct Current (DC) to sub-THz • Deploy new metrics for characterizing low distortion levels in broadband systems in both the frequency and time domain • Validate measurements for next-generation multiple antenna systems • Develop and validate automated test vehicles for free-space and probe-based measurements at 6G data rates
Resource Requirements	• Wide-band sources with advanced modulation capabilities • Expertise in integrated and free-field measurements and modeling • Expertise in test automation
Standards Contribution	• IEEE working groups (e.g., IEEE P287, P1765, P2822) on material characterization and calibration methods at high frequencies using on wafer and over-the-air measurements • Measurement standards to support fundamental communications above 100GHz • International Electrotechnical Commission (IEC) committees
Success Measures (KPIs)	• Industry use/adoption of CTL calibration methods, standards, and distortion metrics for 6G antennas, components, materials, and circuits • Demonstration of SI-traceable probe at sub-THz or THz frequencies • Dissemination of high-frequency material properties through publications and/or database contributions • Deliver calibrations/special tests for advanced phased-array and multi-element antennas

Roadmap Impact

Roadmaps deliver clear strategic value by aligning research efforts with the highest priority stakeholder needs in technology, standards, and measurement science. Through structured planning and external collaboration, they enable effective resource allocation, eliminate redundant efforts, and position CTL to lead in domains with unique value. The planning process fosters staff development, sharpens stakeholder communication, and reinforces the case for future funding. Ultimately, the roadmap elevates CTL's national leadership in measurement science and innovation.

Bridging Research to Deployment

The roadmap creates a seamless pipeline from research concepts to operational 6G systems by embedding openness, traceability, and interoperability into its core strategies. Open datasets paired with standardized measurement methodologies will enable research reproducibility across laboratories, while interoperable testbeds will allow industry and academia to validate solutions in realistic, multi-vendor environments. By reducing the "translation gap" between prototypes and deployable products, these assets will help U.S. innovators move solutions from concept to commercialization faster, lowering integration risks and deployment costs.

Public Safety and Mission Critical Readiness

The roadmap specifically synchronizes technical R&D with the operational mission of the U.S. government, defense, and first responders. This entails NTN/TN integration for disaster area continuity, D2D communications for infrastructure-less operation, ISAC for advanced situational awareness, and ZT architectures for uncompromised security. Incorporating these capabilities into 6G from the beginning keeps mission-critical systems operational in degraded, denied, or contested environments, thereby safeguarding lives and national security.

U.S. Competitiveness in High-Frequency Hardware

By advancing SI-traceable material measurements, developing sub-THz calibration techniques, and validating novel massive MIMO and 3D beamforming architectures, the roadmap strengthens U.S. leadership in the hardware domain. These innovations will directly support efficient, scalable, and cost-effective production of antennas, RF front ends, and high-frequency components for domestic manufacturing. This approach reduces reliance on foreign supply chains, supports technology sovereignty, and positions U.S. companies as leaders in the emerging global market for sub-THz communication and sensing hardware.

Security and Resilience through Design

As quantum computing and advanced cyber threats loom large, the roadmap integrates security at the architectural level, not an afterthought. This entails early implementation of NIST-certified quantum-resistant cryptography, hybrid encryption methods with multiple layers, and ZT frameworks that can enforce policy continuously across disaggregated and virtualized networks. By dealing with data security, identity, and AI-native threat surfaces early on, the roadmap keeps

6G networks and applications secure against both today's and tomorrow's attack surfaces—protecting national infrastructure and public confidence.

Appendix A: Additional Gaps List

In partnership with external stakeholders and internal SMEs, CTL drafted the following gaps in addition to gaps listed in 6G Communications Gaps section earlier in the roadmap. CTL determined that the gaps below were covered by other gaps, were not within the scope of the current roadmap and/or should be moved to a different roadmap topic area. Their inclusion in the roadmap provides additional context to the broad discussions and depth of analysis conducted on 6G Communications research and technology needs.

Additional Gaps Discussed

Open/Service-Enabled Architecture: The continuous move towards a more open, API-based, network architecture will enable the network to be more flexible and resilient. The on-going work in Open RAN is a step forward to disaggregate the RAN, but its value is still being questioned because many operators have already invested in 5G solutions that may not be compatible with Open RAN. Therefore, 6G is viewed as the technology to embrace many of the Open RAN architecture concepts, such as new interfaces, Radio Intelligent Controllers (RICs), and disaggregated Service Management and Orchestration (SMO). Additional research is also needed to develop a Network As a Service (NaaS) architecture that will support new functionalities such as positioning and sensing services.

Closing this gap would require participation in the O-RAN Alliance and 3GPP standardization efforts to ensure consistency across the various architectures and work with industry to reduce duplicative work.

S-Parameter, Power, and Wafer-Level Metrology: High-frequency circuit performance depends on precise S-parameter and power measurements, especially for devices like amplifiers, filters, and antennas. However, the industry currently faces inconsistent definitions and calibration practices particularly for on-wafer measurements where vendors use conflicting impedance standards. This lack of alignment introduces measurement errors and hinders interoperability. Moreover, few tools exist for traceable, high-frequency power measurements at the wafer level, which is increasingly important for densely integrated systems. Without traceable calibrations for on-wafer and packaged devices, it is difficult to compare measurements across labs, slowing down the development and validation of critical 6G components.

Closing this gap would require the establishment of national standards for S-parameters and power, thus harmonizing impedance definitions and providing wafer-level calibration protocols that are vendor-neutral and internationally aligned.

Performance of Cooperative Sensing (Monostatic, Bistatic, Multistatic): ISAC systems are expected to leverage cooperative sensing architectures such as monostatic, bistatic, and multistatic configurations where multiple nodes coordinate to detect and track objects in complex environments. These systems can improve coverage, resolution, and robustness by combining data from multiple perspectives. However, cooperative sensing introduces significant challenges in time synchronization, calibration, and data fusion. In particular, multistatic configurations must deal with heterogeneous hardware, clock drift, propagation delays, and spatial diversity all of which affect sensing accuracy and latency. There is currently a lack of validated channel models, reference data, and system-level testbeds that capture the diversity and complexity of cooperative ISAC. Additionally, data fusion across multiple nodes is computationally intensive and may not meet real-time requirements without optimization. There is limited understanding of the trade-offs between latency, accuracy, and computational cost in practical ISAC networks. The absence of standard test procedures and performance metrics for cooperative sensing scenarios hinders innovation and delays adoption.

Closing this gap would require the development of measurement and modeling capabilities to evaluate cooperative sensing configurations, focusing on precise timing, calibration, and data fusion validation. CTL will use those capabilities to develop and disseminate reference algorithms, publish performance baselines, and assist in defining metrics that assess sensing fusion accuracy, latency, and robustness in diverse RF environments.

AI for RAN: In the Radio Access Network (RAN), AI is set to revolutionize signal processing by enabling machine learning-based receivers that can adaptively perform tasks such as channel estimation, equalization, and demapping. These innovative air interfaces will rely on machine learning models integrated into physical layer components and hardware accelerators that facilitate real-time inference. For ISAC, AI/ML algorithms will also be used to dynamically allocate resources and extract features from shared waveforms. To achieve this, it is crucial to develop hardware co-design approaches that integrate AI models with Digital Signal Processing (DSP) pipelines, as well as curate datasets for both communication and sensing. Several specific challenges need to be addressed, including the absence of standardized data formats for training models and the difficulty of collecting representative joint communication and sensing data in realistic environments. On the hardware side, additional work is also needed to integrate machine learning accelerators into radio front ends that are constrained by power and latency. Moreover, there are ongoing questions regarding how to maintain the transferability and robustness of ML models across varying radio frequency (RF) environments and conditions, as well as how to validate the reliability of these models under different channel dynamics.

Closing this gap would require the development of calibration techniques for AI-augmented receivers, define standardized test cases for ISAC, and provide datasets to enable the performance evaluation of AI models under realistic RF conditions.

Networking for AI: Beyond using AI for communications, 6G networks must also be optimized to serve AI workloads, including distributed training and real-time inference. This involves providing low-latency, high-reliability connections for edge computing, allocating network slices for AI tasks, and supporting the dynamic orchestration of AI services. Networking for AI requires infrastructure capable of adapting to compute and data distribution needs, efficient transport protocols, and coordination between cloud, edge, and device layers. One of the biggest needs is real-time observability AI workloads are highly dynamic, and the network must sense and respond to changing inference and training demands. ML-aware routing and traffic engineering, especially in support of large-scale federated learning, remain underdeveloped. There is also a lack of standardized interfaces and metrics to assess whether the network is meeting AI workload requirements, including jitter, synchronization, and inference deadlines. Bottlenecks in backhaul and fronthaul can significantly degrade AI service performance, yet tools to analyze these impacts are immature.

Closing this gap would require collaboration with the industry to develop and standardize a 6G architecture supporting AI workflows, leveraging its AI/ML and federated learning expertise.

AI for Security: Security in AI-enabled 6G systems is both a use case and a challenge. AI will be used to enhance security through intelligent threat detection, anomaly analysis, and predictive defense. At the same time, the AI models themselves may be vulnerable to attacks such as poisoning, evasion, or model inversion. Securing AI models and ensuring trustworthy operation is therefore a high priority. Federated and split learning approaches are expected to be deployed not only to improve scalability but also to enable privacy-preserving collaborative model training, especially in distributed and edge-based environments. However, ensuring the integrity of distributed learning, and detecting poisoned or malicious updates in real-time, is still an open problem. Robust model design, auditability, and the ability to reason about adversarial risk across the network stack are also emerging concerns. Additionally, more research is needed to define common standards for evaluating AI model robustness or frameworks for simulating complex attack scenarios at scale.

Closing this gap would require the development of reference datasets for adversarial testing, standardized testing environments for AI resilience, and conformance metrics for secure AI deployment in communications infrastructure.

Appendix B: Existing Projects and Current Capabilities

There are a variety of projects that showcase CTL's capabilities in 6G Communications. Many of these projects are well-positioned to contribute to the future work that the 6G communication goals will require to advance communications technology. Whether through direct or indirect means, these projects contribute to the research necessary to address 6G communications goals adequately.

Integrated Sensing and Communication

Future wireless networks must seamlessly integrate sensing and communication to enable new capabilities such as object detection, localization, and environmental awareness. CTL is developing an ISAC channel realization framework that builds on its Quasi-Deterministic (Q-D) channel model, incorporating human motion models to enhance presence detection and localization. The framework also uses advanced signal processing techniques allowing for precise motion tracking. These innovations will support applications in public safety, robotics, and industrial automation, enhancing situational awareness and enabling intelligent networked environments that improve efficiency and safety in various sectors.

Open-RAN

The shift toward open, interoperable network architectures requires rigorous testing and measurement required for performance and security. CTL is advancing Open-RAN research through its Open-Source Wireless Testbed, enabling fine-tuned evaluations of ML-driven network automation and optimization. Additionally, CTL is leading efforts to integrate Zero Trust Networks into O-RAN Alliance standards, strengthening protections for virtualized and disaggregated network components. This research ensures that Open-RAN solutions will provide resilient and scalable infrastructure for future networks by promoting vendor diversity, enhancing network security, and supporting flexible, cost-effective 6G deployment.

Trustworthiness

Future 6G networks must be resilient against emerging cybersecurity threats while solidifying data integrity and system reliability. The Trustworthy Networks Research program at CTL addresses systemic vulnerabilities in network infrastructure, advancing security, privacy, and resilience. These advancements will be essential for securing mission-critical applications in defense, healthcare, and smart cities, where network reliability and trustworthiness are paramount.

Sidelink (Device-to-Device)

Sidelink, or D2D communication, is an enabler for resilient, infrastructure-independent networks. CTL actively contributes to 3GPP standardization efforts for multi-hop D2D communication, extending coverage in scenarios where traditional network infrastructure is unavailable. This research is particularly valuable for first responders, military operations, and remote area connectivity, guaranteeing seamless and reliable communication in challenging network environments. This work will strengthen emergency response efforts and improve network resilience in defense applications by enabling direct, multi-hop communication between devices.

AI and ML or AI Native

As networks become increasingly complex, AI-driven automation is essential for optimizing performance and resource management. CTL is developing AI and ML-based approaches for 6G networks with the Data-Driven Network Optimization project, creating reference datasets that enable robust AI model training and authentication. These datasets will allow wireless systems to dynamically adapt to changing environments, improving efficiency and spectrum utilization. AI-native 6G networks will reduce operational costs, enhance reliability, and deliver seamless connectivity for advanced applications across industries by enabling self-optimizing, highly adaptive communication systems.

Spectrum and Hardware

CTL is also pioneering advancements in 6G spectrum and hardware research to enable high-performance, reliable wireless communications. In spectrum, it is redefining propagation models and measurement techniques through NextG Channel Measurement and Modeling to support industry adoption of mmWave and THz frequencies, assuring accurate characterization of high-frequency wireless environments. Additionally, CTL wireless coexistence research develops advanced modeling and measurement methodologies to optimize spectrum sharing, enhancing efficiency and minimizing interference across wireless systems. In hardware, the 6G Traceability program extends phase traceability up to 220 GHz, supporting international standardization efforts and guaranteeing accurate, high-frequency network performance measurements. Additionally, Over The Air (OTA) testing establishes rigorous metrology for assessing wireless device performance in complex environments, supporting industry needs for high-speed, low-latency applications such as telemedicine and remote operations. These efforts drive the evolution of 6G, certifying seamless spectrum utilization and robust network architectures for next-generation wireless services.

Appendix C: Meeting Participant List

The following list of CTL staff and external stakeholders contributed to roadmap development through interviews, data calls, and panels.

Ari Feldman	CTL Director
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Ozge Koymen	Qualcomm
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Ardavan Tehrani	Samsung

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This manuscript was edited with the assistance of Grammarly, developed by Superhuman Platform Inc. Grammarly was used to refine language, improve clarity, and enhance readability in accordance with the authors' instructions. All content, scientific claims, and conclusions have been reviewed and verified by the authors to ensure accuracy and originality.