Communications Technology Laboratory

Spectrum Science 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 Spectrum Science Roadmap (the roadmap) to prioritize future investments in spectrum science research that align with high-priority stakeholder needs and are in line with CTL's mission: *"Advance connectivity. Enhance performance. Grow our economy. Improve lives."*

Spectrum Science Defined

A shared and clear understanding of spectrum science is essential for establishing research objectives and priorities. For this roadmap, CTL defines spectrum science as the multidisciplinary study and analysis of properties, utilization, and management of the electromagnetic - including optical – spectrum. It involves understanding how electromagnetic and optical waves propagate, interact with different environments, and are harnessed for communication, sensing, and other applications. Research in spectrum science addresses both theoretical foundations and practical implementations, aiming to optimize spectrum use, improve wireless technologies, and ensure coexistence among various users.

NIST CTL conducts research in spectrum science in four focus areas: State of the Art Measurement Techniques to assess the utilization of the spectrum, evaluation of methods that optimize the use of the spectrum in the form of spectrum sharing and wireless coexistence, Dynamic Systems Metrology, and Optical Time Transfer. These areas combine to bring an integrated understanding of the spectrum to deliver trusted data to anticipate and enable the dynamism of tomorrow's spectrum landscape.

High-Level R&D Goals for 6G Communications

The roadmap defines five goals, listed without specific order, for CTL research to maximize CTL impact given anticipated trends, innovations, and activities taking place across the spectrum of science research and development (R&D) domain. Six months of external stakeholder engagement sessions informed NIST research goals that are 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 spectrum science over the next five to seven years:

- **Demonstrate Femtosecond Timing Networks:** CTL will contribute to the creation of ultra-precise timing systems that can synchronize clocks across significant distances (e.g., ground to satellites thousands of kilometers away) with accuracy down to femtoseconds (one quadrillionth of a second). CTL will accomplish this goal by working toward a next-generation global timing network that uses light-based (optical) and quantum technologies to share time signals with meticulous precision.

- **Develop Ultra-Sensitive Quantum Enhanced Spectrum Measurement Tools and Techniques:** CTL will focus on advancing quantum technologies to enable the detection and measurement of extremely weak signals with high precision, even in complex or noisy environments. CTL will develop new methods to extend sensing capabilities into underused regions of the spectrum and across a wide range of distances, from meters to thousands of kilometers. These technologies will effectively increase the sensitivity of sensors, allowing them to detect subtle changes or faint signals that would otherwise go unnoticed, supporting applications that require precise environmental awareness across large or dynamic spaces.
- **Increase Spectrum Coexistence Reliability and Performance:** CTL will conduct research to enhance the seamless operation of diverse wireless technologies within the same spectrum bands without causing interference or performance degradation. As the number of spectrum users continues to grow, devices (e.g., smartphones, satellites, radar systems) must share the same spectrum efficiently and reliably. CTL will work to develop standards, measurement methods, and enabling technologies that allow these systems to coexist, maintaining high performance while minimizing data loss, latency, and interference across increasingly crowded and complex spectrum environments.
- **Develop a Harmonized Aggregate Emissions Definition:** Collaborate with spectrum stakeholders to create a shared and scientifically sound definition of aggregate emissions, supporting smarter, more reliable spectrum sharing between commercial and federal users.
- **Define Standards for Spectrum and Environment Sensing:** Define clear standards for reliable and traceable spectrum data, from measurement methods to data quality and analysis, ensuring spectrum information is consistent, accurate, and scientifically grounded.

Each goal addresses a set of stakeholder-identified needs within the spectrum science community to spur innovation and deliver creative solutions to complex communications challenges.

The document includes an *Introduction* that outlines the purpose, definitions, and methodology used for this effort; a review of *Key Trends and Drivers* influencing spectrum-related research; an *analysis of Spectrum Science Gaps*; and *Goals and Implementation Pathways* describing the factors motivating spectrum science research and the strategies for addressing identified gaps. The *Appendix* lists contributing participants and identifies additional spectrum science gaps that do not directly align with the priority CTL R&D goals described in this roadmap. Each section offers detailed insights into the findings and analysis that support the roadmap's structure and direction.

Introduction

The National Institute of Standards and Technology (NIST) Communications Technology Laboratory (CTL) developed six roadmaps to guide its internal 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

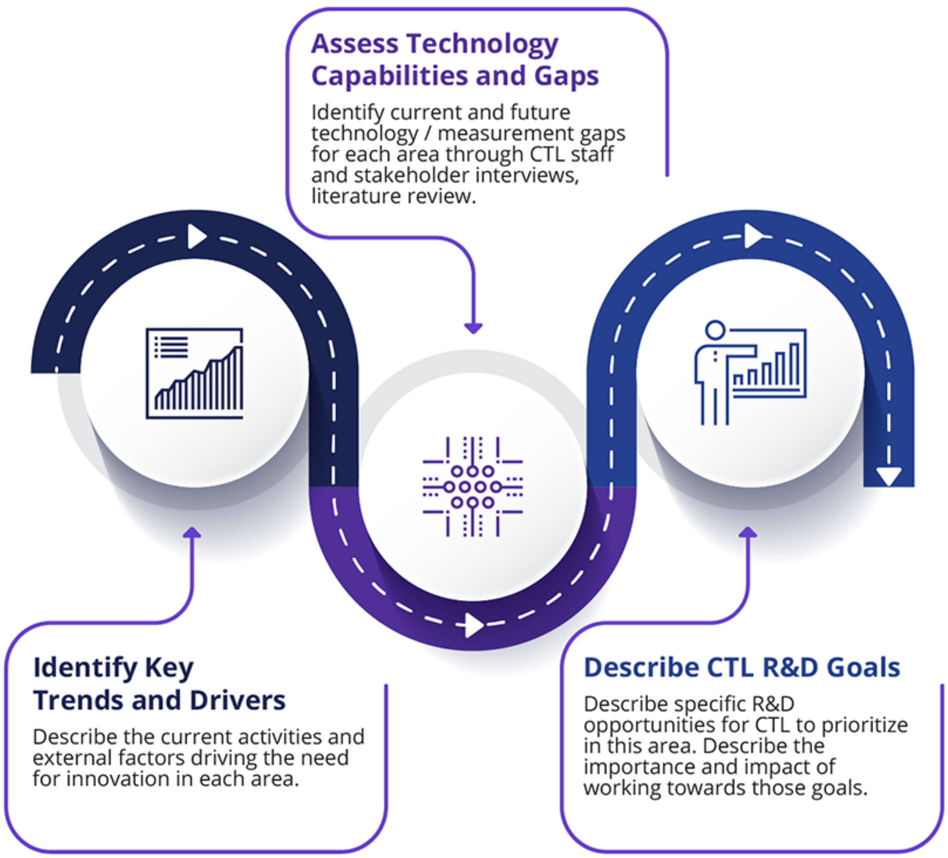
By developing these roadmaps, CTL aims to achieve the following:

- 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 investment.
- 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 spectrum science research and development (R&D) domain.

Developing the Spectrum Science Roadmap required a deliberate, structured, and collaborative multi-phase process to ensure alignment with the overall CTL mission and stakeholder priorities. From November 2024 to May 2025, three organizational planning sessions, composed of Laboratory Leadership Team (LLT), Division Chiefs (DCs), and POCs, established the roadmap framework, refined gap areas, and finalized R&D goals. CTL conducted internal interviews with CTL SMEs to determine current capabilities and any applicable limitations. Additionally, external stakeholders were consulted through a three-panel engagement to identify, prioritize, and validate

R&D gaps and research opportunities. These inputs were synthesized into themed gap categories, informing goal development, resource planning, and action steps that culminated in a consolidated roadmap draft designed, developed, and vetted by CTL staff and leadership.



Spectrum Science Roadmap Definitions

Point of Contact (POC)

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 (SMEs)

Subject Matter Experts, or SMEs, are internal CTL staff who have a breadth and depth of knowledge within the topic area.

External Experts

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 other government such as Federal agencies or Federally Funded Research and Development Centers.

Key Trends and Drivers

External forces, including industry shifts, regulations, and new technologies, that shape stakeholder needs and research priorities.

Gap

An industry-wide, clearly defined deficiency in scientific knowledge, technology capabilities, or infrastructure that prevents the fulfillment of emerging requirements, stakeholder needs, or strategic objectives.

Goal

Prioritized research objectives that address critical gaps, align with the lab's mission, and outline measurable outcomes.

Methodology for Roadmap Development

CTL implemented a multi-phase strategic planning approach between November 2024 and 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 established the overarching framework and identified five priority topic areas, including spectrum science. Strategic Planning Session Two focused on defining CTL's external stakeholder engagement strategy and refining research gap lists. During Strategic Planning Session Three, CTL designed R&D goals, aligned resource requirements, and identified cross-cutting strategic themes across each roadmap topic area.

To build a robust foundation for these discussions, CTL conducted a literature review and internal interviews to document current capabilities, determine technical gaps, understand prior research efforts, and identify opportunities for future research. 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 launched an external engagement effort involving three structured panel discussions per roadmap topic, with additional interviews as needed.

During Panel 1, external experts reviewed the initial list of gaps created by CTL staff and identified additional R&D gaps from industry and academic perspectives. In Panel 2, external experts prioritized these gaps based on importance, urgency, and overall impact, while Panel 3 explored emerging research opportunities and technology trends. CTL selected participants for their level of expertise, prior collaboration with NIST or CTL, understanding of industry needs, and future-oriented insights, ensuring a broad and relevant knowledge base spanning topics including telecommunications sciences, astrophysics, and radio astronomy.

External stakeholders emphasized the critical need for establishing trusted datasets to promote greater standardization and rigor in spectrum science, alongside more practical standards for addressing aggregate interference. Stakeholders consistently stated that NIST's neutrality helps position CTL well to lead in standardized measurement techniques, creating realistic testing environments, and enabling measurement-informed policy. Stakeholder priorities included advancing dynamic spectrum sharing, building trust in spectrum data, enabling coexistence in heterogeneous applications (with a call to expand this to include active-passive scenarios), and addressing challenges related to antenna beamforming, where rapid technological adoption is outpacing regulatory frameworks. Across these areas, stakeholders highlighted opportunities for NIST to drive innovation and provide leadership in developing the trusted measurements and data necessary for future spectrum accessibility.

Following the stakeholder panels, CTL synthesized all internal and external gap inputs into thematic categories such as measurements, datasets, and standards. Internal SMEs prioritized gaps using a similar matrix to external experts, ranking each gap based on urgency, impact, and importance, as well as the unique ability of CTL to address each need. From this prioritized list, roadmap teams crafted draft R&D goals for each topic area, each accompanied by a clear problem statement and aligned with measurable outcomes. CTL staff collaborated on these goals 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. 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

A variety of external factors shape spectrum science research, such as industry developments, regulatory updates, emerging technologies, and strategic national priorities. These trends and drivers, drawn from observation of developments in communications technology, literature reviews, and external stakeholder engagements, influence the research priorities described in this roadmap. Identifying trends and drivers enables CTL to identify gaps and set R&D goals that complement technical advances and research opportunities within the spectrum science ecosystem.

The following six trend areas emerged as the most impactful influences on spectrum science research: (1) advances in communications architecture, (2) realistic modeling and validation, (3) dynamic spectrum sharing, (4) data sharing and reproducibility, (5) collaboration and R&D infrastructure, and (6) AI/ML-enabled testing environments. These trends reflect technological, regulatory, and methodological shifts across the spectrum ecosystem.

Advances in Communications Architecture

Real-world design goals drive advances in communications architecture by demanding reliable, low-latency, and context-aware systems.[1] These capabilities seek access to mid- and high-band spectrum and introduce complexity in managing dynamic, non-stationary environments.[2] External drivers influencing spectrum science include global competition over 6G leadership and the need for interoperable systems and real-time / on-demand access to spectrum.[3] Sensing, adaptive, and open architectures advance spectrum science by enabling scalable testing and guiding the design of NextG communication and sensing systems.

Realistic Modeling and Validation

There is a growing complexity in spectrum environments due to the multiplication of wireless devices and applications vying for access. In this competitive environment, there is a need for accurate and trustworthy modeling to support dynamic spectrum sharing and coexistence.[4] Moving toward data-driven and measurement-validated, realistic simulation and modeling for interference, propagation, and dynamic spectrum environments increases opportunities for improved predictive capabilities and enhances scientific accuracy. As machine learning and AI tools are being incorporated there is a need to provide trusted and high-quality measurement datasets across diverse environments, to enable rigorous machine learning models for scalability, data accuracy, and traceability.[5]

Dynamic Spectrum Sharing (DSS)

Dynamic Spectrum Sharing (DSS) is anticipated to become central to meeting the growing demand for spectrum and enabling real-time multi-user access. Increasing pressure from additional users and varying device types and applications, as well as evolving regulatory support, furthers the need to provide efficient access to spectrum in congested bands.[5] Industry and academic researchers tend to focus on challenges to interoperability and control-plane latency while also addressing security issues in shared environments to enable progress in DSS.[4] CTL's goal, *Increase Spectrum Coexistence Reliability and Performance*, drives for measurement methods and developing recommendations for quantifying and assessing core capabilities in spectrum sharing, addressing the need for measurement-based validation of DSS. The 6G roadmap has additional components towards DSS, including the convergence of sensing, communication, and non-terrestrial networks.

Data Sharing and Reproducibility

Access to high quality, labeled, traceable test data and reproducible research protocols is foundational to spectrum innovation and research. Increasing scientific complexity and a need for trust in regulations provide additional motivation for producing traceable and reproducible datasets. There are increasing opportunities for cross-sector research acceleration through sharing and producing traceable datasets, which improves transparency and provides support for setting standards and best practices.[5] While challenges persist in data privacy, metadata standardization, and establishing legal and data quality frameworks for sharing data across stakeholders, traceable datasets remain a priority for the spectrum science community at large.[4]

Collaboration and R&D Infrastructure

Policy initiatives aimed at spectrum science innovation encourage collaboration across academia, industry, and government to drive innovation and advancement in spectrum science.[6] There is a need for leadership towards scalable coexistence protocols, frameworks that are adoptable through standards and can account for the requirements of different stakeholder groups. Challenges arise when attempting to harmonize stakeholder goals and agendas, and concerns over intellectual property could discourage potential partnerships.[4]

Artificial Intelligence (AI), Machine Learning (ML), and Agile Testing Environments

Use of Artificial Intelligence and Machine Learning (AI/ML) is pervasive and readily accessible. All too often the underlying data is inappropriate to support scalable, repeatable insights into complex R&D system validation and testing. To overcome the deficit and build towards faster development cycles and robust testing of spectrum technologies there is a need for reproducible, realistic, and corroborated data sets. Similarly, dynamic spectrum environments, while ripe for AI/ML advances, require consistent, high-quality training and validation data for functional adoption of AI/ML models.[5] Underlying the appropriate use of AI/ML in high technology areas is the distribution of trusted datasets. CTL sees an opportunity for applying state of the art developments to capture well characterized and labeled datasets from multi-domain, heterogeneous sensor networks.

Summary of Key Trends

The spectrum landscape is shaped by the need for trusted, reproducible datasets, realistic testing environments, stakeholder engagement, and scientific leadership. Collectively, these trends highlight the critical connection between technical and collaborative drivers that will determine the scalability and reliability of spectrum access and guide CTL's long-term vision for spectrum science.

Spectrum Science Gaps

The identification and prioritization of research gaps ensure that spectrum science efforts remain aligned with the most impactful needs of CTL's stakeholders. Gaps represent areas where existing knowledge, methodologies, or technologies may fall short of the requirements to support emerging communications systems and scientific demands. By focusing on these critical areas, CTL can allocate resources more strategically, build upon unique capabilities, and guide NIST research that closes these gaps in support of national spectrum objectives.

CTL's gap identification process incorporated multiple layers of internal and external feedback, resulting in research goals that reflect both CTL strengths and the broader needs of the spectrum science community.

When providing verbal feedback, panel participants commented on which gaps were highest priority for industry, in addition to which gaps they believed CTL could most effectively address. External experts agreed that CTL is uniquely qualified to address the following gaps:

- Aggregate Interference
- Realistic Testing Environments
- Standardized Measurement Techniques
- Establish Trust in Spectrum Data
- Best Practices for Broad Spectrum Electromagnetic Interference (EMI) Testing

Through both internal and external interviews, external experts and SMEs identified a total of 29 gaps in spectrum science. After rigorous review during Strategic Planning Session Three, spectrum science POCs and SMEs selected 10 top-priority gaps that CTL can address within the next five to seven years. A full list of the gaps considered are shown in Appendix A. The chosen gaps have precise alignment with spectrum science key trends and drivers, speaking to the depth and breadth of expertise within internal and external SME groups. These 10 gaps drive and inform the R&D goals crafted by CTL to guide research efforts, addressing critical research needs in spectrum science. Each goal identifies the gaps addressed, and many gaps address more than one goal. Some of these goals address gaps that were not originally identified in the road mapping process. This came as a result of careful consideration of the impact of achieving the goal and considering what additional gaps might also be addressed along the way.

Spectrum Sharing

Dynamic Spectrum Sharing and Cognitive Spectrum Access: Research is needed to improve the community's understanding of what's possible and practical with DSS and cognitive spectrum access. This includes work to show whether DSS technologies perform as effectively and reliably in practical, real-world telecommunications deployments as they do in controlled lab settings. DSS validation, which has relied on controlled lab environments as well as real-world deployments, still struggles to account for challenging factors impacting spectrum environments such as uncoordinated users, interference dynamics, and unpredictable traffic patterns. The technology is constrained by the need for more sophisticated cognitive spectrum access protocols and resource management strategies that can leverage real-time interference information. A significant body of work is dedicated towards algorithms that can dynamically allocate spectrum resources, adjust transmission parameters (e.g., power, modulation), and coordinate with other users to minimize interference in a distributed and decentralized manner. The critical aspect for NIST is to develop real-world-backed measurement methods to quantify the effectiveness of these types of sharing and spectrum access architectures to allow adopters to differentiate between or improve upon methods.

Coexistence in Heterogeneous Applications: The increasing diversity of spectrum users, ranging from high-throughput broadband services (e.g., active-active Wi-Fi and cellular deployments) to latency-sensitive Internet of Things (IoT) and passive or active sensing systems (e.g., active-passive communications impacting remote sensing), creates coexistence challenges. As DSS systems become more localized, the potential for conflicts between heterogeneous applications grows. There is a lack of coexistence protocols and frameworks that enable diverse applications to share spectrum effectively while maintaining performance, particularly in environments with mixed legacy, heterogenous communication protocols, and critical systems (e.g., radar, defense, and radio astronomy observations potentially impacted by active services).

Measurement Methods and Techniques

Realistic Testing Environments: Current measurement methods often rely on simplified or idealized testing environments that don't accurately reflect the complexity of real-world spectrum conditions. Research should focus on developing realistic testing environments that incorporate factors like diverse signal types, dynamic spectrum usage, multipath propagation, and varying interference levels.

Standardized Measurement Techniques: The lack of standardized measurement techniques and frameworks for assessing modern communication systems for interference susceptibility, operating conditions, and spectrum utilization hinders the comparison of results across different studies and devices. Measurement techniques used to evaluate spectrum interference and utilization often use inconsistent definitions, metrics, or reference datasets. This inconsistency makes it difficult to generalize measurement results across device platforms or reliably assess the performance of different spectrum sharing systems, which can lead to a lack of confidence in specific performance claims and the inability to validate results. Research should focus on developing standardized measurement protocols and metrics, such as quantifying effective utilization of modern commercial off-the-shelf (COTS) communication systems that can be used to generate consistent and comparable data across different testing environments and research groups. This research will enable more meaningful comparisons and facilitate the development of effective, interoperable spectrum sharing strategies. This effort must also address measurement statistical error analysis.

Establish Trust in Spectrum Data: There is a lack of standardized measurement techniques for acquiring spectrum data, and an absence of advanced analytics for interpreting it. Building community trust in scientific measurement results requires addressing those two areas. A large volume of measurements with robust statistical representation is essential to establish a foundation of trusted data and provide accurate information for spectrum-sharing applications.

This information demands rigorous, standardized methodologies for measurement procedures, error analysis, and experimental setup validated by an independent third party to ensure credible and repeatable results. In parallel, domain-specific datasets tailored to spectrum management must be developed, along with AI tools to analyze, interpret, and optimize spectrum usage patterns while maintaining transparency and user trust. Advanced analytics should support the identification of trends, anomaly detection, and actionable insights for decision-making, including the development of visualization tools and predictive models.

Measurements That Support the Ability to Quantify Interference

Aggregate Interference: Calculating, predicting, and managing aggregate interference, which arises from the combined impact of multiple, potentially low-power emitters operating in a shared frequency band, remains a significant challenge, especially in dense environments and dynamic spectrum sharing scenarios. The challenge encourages further development in advanced modeling, analysis, and spectrum measurement techniques, including proof of effect in control settings. There is a broad need to accurately predict the cumulative impact of aggregate interference on different types of systems and applications, including controls and checks for aggregate interference. This process could involve creating defined measurement methods and techniques, developing interference models, novel methods to quantify spectrum use of contributors, distributed sensing, and collaborative interference mitigation strategies.

Interference Characterization, Impact Prediction, and Intelligent Sensing: Current methods often struggle to accurately and rapidly characterize and predict the changing interference environment in DSS. They also may not adequately capture the complex interactions between interference waveforms and broad topologies of receiver types and protocols. In addition, it remains challenging to predict the characteristics and impact of undesired signals in dense spectrum sharing scenarios with diverse emitters. Research should focus on developing intelligent sensing techniques and models that can automatically and accurately detect, classify, and characterize different types of signals, adapt to changing spectrum conditions, and identify anomalies and potential interference sources, locations, short-term behavior, and statistical properties. This research could involve developing signal recognition techniques, anomaly detection algorithms, dynamic interference modeling, or simulation frameworks, and could leverage machine learning, cognitive radio technologies, and advanced signal processing algorithms.

Improved Channel Modeling

Propagation Prediction: Current propagation models often struggle to accurately predict signal behavior in complex and dynamic environments, such as urban canyons, indoor environments, and areas with varying terrain and vegetation. Research is needed to develop advanced propagation models that incorporate real-time environmental data, such as weather patterns, foliage density, and building layouts, to improve prediction accuracy in diverse and changing environments. This process could involve leveraging ray-tracing techniques, machine learning, and crowdsourced data.

Regulatory Framework Alignment

Measurement-Informed Policy Development Processes: The rapid advancement of spectrum-sharing technology has outpaced regulatory framework development, creating a disconnect that limits deployment and scalability. Research is needed to drive down risk in adoption to support emerging spectrum-sharing paradigms. Collaborative efforts should focus on creating proactive, technology-informed policy development processes to harmonize technological capabilities with regulatory requirements.

Developing Robust Measurement Methods and Data Collection Strategies: There is a need for accurate and comprehensive data about spectrum usage. Spectrum regulators have a desire for these data including, interference patterns, and system performance. Investing in standardized measurement techniques and data analysis tools could improve the data quality regulators may have at their disposal in conjunction with filings they rely on to make informed decisions about spectrum sharing rules and policies.

Research Goals and Implementation Pathways

CTL reviewed stakeholder-identified trends, drivers, and technology gaps impacting the spectrum science research domain to identify five critical research goals for the laboratory's spectrum science research over the next five to seven years. Each goal targets a set of prioritized research needs and charts a clear path forward for scientific advancement, standards alignment, and cross-sector impact.

Each goal description includes three core components: 1) supporting gaps, which explain the technical challenges and unmet needs the goal aims to resolve; 2) action items, which outline the specific steps required to achieve results, such as developing new tools, refining measurement techniques, or establishing collaborations; and 3) resource requirements, which identify the personnel, facilities, and funding necessary to execute the work effectively. Together, these elements ensure traceability between the CTL high-level strategy and the operational decisions that shape current and future research investments.

Goals also include anticipated contributions to standards development, such as creating metrology protocols, participating in standards bodies, or releasing traceable datasets. Success measures help track technical milestones and evaluate progress based on peer-reviewed outputs, standards impact, and stakeholder engagement.

The **five research goals** focus on advancing capabilities in the following areas of spectrum science:

- **Goal 1: Demonstrate Femtosecond Timing Networks:** Develop a compact, low-power system that can send ultra-precise timing signals between Earth and satellites in medium-Earth orbit.
- **Goal 2: Develop Ultra-Sensitive Quantum Enhanced Measurement Tools and Techniques:** Develop advanced tools and techniques that make it possible to enhance molecular and atomic measurements with greater speed and accuracy over very large distances.
- **Goal 3: Increase Spectrum Coexistence Reliability and Performance:** Develop novel approaches to help diverse technologies share spectrum without disruption, ensuring reliable performance even in busy, mixed-use environments.
- **Goal 4: Develop a Harmonized Aggregate Emissions Definition:** Collaborate with spectrum stakeholders to create a shared and scientifically sound definition of aggregate emissions, supporting smarter, more reliable spectrum sharing between commercial and federal users.
- **Goal 5: Define Standards for Spectrum and Environment Sensing:** Define clear standards for reliable and traceable spectrum data, from measurement methods to data quality and analysis, ensuring spectrum information is consistent, accurate, and scientifically grounded.

These goals focus CTL's efforts on high-impact outcomes that respond to urgent needs in the spectrum ecosystem, while leveraging the lab's unique strengths in measurement science, neutrality, and stakeholder collaboration.

Goal 1: Demonstrate Femtosecond Timing Networks

Femtosecond Timing Networks: Ground-to-medium-Earth orbit (MEO) time transfer systems for national and intercontinental femtosecond timing networks: CTL will develop next-generation optical clock networks, evolving quantum sensor networks, and next-generation distributed coherent sensing requiring femtosecond timing distributed throughout continents. Systems must be low Size, Weight, and Power (SWaP), turn-key, capable of independent startup and quickly establishing quantum-limited timing links to fast-moving satellite targets. Field demonstrations with networks of quantum sensors and tech transfer to industry partners will ensure technology readiness level.

Why is this a priority?

Developing ground-to-MEO femtosecond timing networks contributes to advances in communications architecture and growing R&D infrastructure collaboration. These systems require low-SWaP, rapidly deployable timing solutions capable of establishing quantum-limited links with fast-moving satellites. Precise timing is required for modern telecommunications, navigation and national security. From synchronizing cell towers to avoid dropped calls and data errors, to satellites and GPS, which depend on accurate clocks to pinpoint location, precise timing is critical to ensuring networks support technological advances like 6G, autonomous vehicles, and quantum communications. Addressing this goal supports U.S. competitiveness in quantum and NextG, while also improving system security and interoperability. In addition to enabling these advances, this goal is a priority for NIST and industry as its successful implementation contributes to:

- **Increased Precision:** Developing next-generation and quantum-enhanced optical clock networks improves precision across platforms like GPS, telecommunications, and satellites by building on the superior accuracy of optical atomic clocks. These clocks outperform traditional microwave clocks by several orders of magnitude, delivering the ultra-stable timing required for femtosecond-level synchronization, which in turn enables more accurate positioning and coordination in complex, distributed systems.
- **Increased Reliability:** These advancements in optical timekeeping could enable sub-centimeter location accuracy, even in challenging environments like underground facilities, indoors, or dense urban areas where GPS signals are weak or unavailable. These capabilities are essential for industries relying on time-sensitive infrastructures such as aerospace, telecommunications, and autonomous systems.[7]
- **Miniaturization and Transportability:** Developing low-SWaP systems is critical for deployment on satellites, drones, or portable platforms, where space is limited, and energy reservation is essential. Achieving femtosecond precision over free-space optical links ensures robust communication and coherent sensing across vast distances, enabling applications like distributed radar and secure quantum communications.[7] Providing more

portable systems improves navigation and positioning and enables more resilient, high-capacity communications, leveraging time-frequency coherence in optical networks.

- **Support for U.S. Strategic Priorities:** Next-generation timing infrastructure helps ensure U.S. leadership in secure communications by providing the ultra-precise, reliable time references needed for encryption, authentication, and coordination across distributed systems, which are capabilities other nations are actively pursuing through advanced satellite navigation systems, optical atomic clock networks, and quantum timing links. It also strengthens U.S. leadership in precision navigation and scientific research. Future wireless standards such as 6G will depend on ultra-precise timing synchronization between base stations, antennas, and user devices to achieve high data rates and ultra-low latency. Investing in these networks aligns with federal priorities for space-based Positioning, Navigation, and Timing (PNT) and economic competitiveness in quantum technologies and NextG communications.[8]

Why NIST?

CTL is uniquely positioned to lead the development of femtosecond-level timing networks, building on NIST's decades of global leadership in precision timekeeping and its role as steward of the U.S. primary time standard. With world-class expertise in optical atomic clocks and advanced optical frequency comb and time-transfer technologies, CTL can translate laboratory precision into field-ready systems capable of reliable timing links over continental and orbital distances. CTL's established calibration services, spectrum measurement infrastructure, and testbeds, combined with its collaboration with industry partners, enable the creation, validation, and deployment of low-SWaP, turn-key optical clock networks for integration into communications, navigation, and sensing systems.

Implementation Pathways

The table below links each spectrum science 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.

Key Trends and Drivers	• Advances in Communications Architecture • Artificial Intelligence (AI), Machine Learning (ML), and Agile Testing Environments
Supporting Gaps	• Integrated Optical Timing Hardware and Optical Communication Hardware • Femtosecond Time-Transfer to Fast Moving Platforms • Demonstration of Quantum Sensor Networks and Space Based Timing Networks
Action Items	• Develop signal tracking and processing required by fast-moving platforms • Integrate controls, signal processing, and communications

	• Technology transfer of critical systems to industry partners • Demonstrating networked quantum sensors over >100 km separation with femtosecond synchronization
Resources Requirements	• Staff expertise in non-linear optics and femtosecond lasers, atmospheric propagation, algorithm design for fast digital control systems. • Partnerships with satellite laser ranging or optical communications stations • Fast FPGA (Field Programmable Gate Array) or RFSoC (Radio Frequency System-on-Chip) support to integrate controls, signals processing, and communications
Standards Contribution	• This work will be critical to continued U.S. participation in the definition of the SI (International System of Units) second.
Success Measures (KPIs)	• Enable quantum geodesy field measurements through parts in 10^18 timing networks • Time dissemination from an aircraft or satellite platform • Qualify the successful space of core femtosecond time transfer hardware

Goal 2: Develop Ultra-Sensitive Quantum Enhanced Measurement Tools and Techniques

Ultra-Sensitive, Quantum Enhanced Measurements: Create Technology and Methodology to Support Field and Industrial Applications of Ultra-Sensitive, Quantum Enhanced Molecular and Atomic Measurements in Novel Spectral Regions and Over Meter to Megameter Length Scales: Techniques such as quantum squeezing, intelligent digital phase-control, and cavity confinement will be used to improve speed and sensitivity of our ability to quantify trace molecular species. This process will result in enhanced applicability of dual-comb spectroscopy in the field and laboratory for agriculture, air quality, wastewater treatment, and industrial processes. By addressing the need for lower SWaP and cost sensors while increasing sensitivity and accuracy, we create infrastructure to meet industry, defense, and public trace gas sensing needs.

Why is this a priority?

Creating technology and methodologies for ultra-sensitive, quantum-enhanced molecular and atomic measurements directly connects to advances in communications architecture and expanding R&D collaboration. Industry increasingly needs high-precision, low-SWaP sensing systems capable of delivering reliable data across large and complex environments, driving demand for spectrum access and architectures that support low-latency, context-aware communications. Progress in this area depends on collaborative efforts among government, academia, and industry to establish shared protocols and align standards for spectrum and environmental sensing research. Addressing this goal strengthens the foundation for scalable, interoperable, and real-time measurement networks, supporting industrial, environmental, and public-sector applications while fostering coordinated innovation across the spectrum science ecosystem. In addition to these advances, this goal is a priority for NIST and industry as its successful implementation contributes to:

- **Increased Sensitivity and Accuracy:** Creating smaller, lighter, more powerful sensors increases sensitivity and accuracy, enabling use in a wide range of environments, including agriculture, healthcare, and space exploration. Low-SWaP instruments that quantify trace gases and biomolecules in the field and on production lines are essential for industry applications. Quantum-enhanced methods (e.g., squeezing, digital phase control, cavity confinement) and dual-comb spectroscopy directly enable faster, more precise measurements over meter-to-megameter paths for precision agriculture, air-quality compliance, and wastewater monitoring.[9]
- **Expanded Portability and Advanced Efficiency:** Expanding portability by decreasing size and weight of measurement technology moves ultra-sensitive spectroscopy from fixed laboratory setups to real-world environments, reducing reliance on large facilities and laboratories to perform accurate research. Portable, low-SWaP instruments make it possible to gather high-quality data in remote or distributed locations (e.g., offshore oil platform, rural agricultural field, industrial sites) where conventional systems are impractical or impossible.[10] This capability extends access to advanced sensing tools, enabling more frequent and widespread monitoring in industrial and environmental applications, including use on drones or wearable devices.[9] This energy efficiency lowers the cost per measurement and enables persistent monitoring, making continuous sensing economically viable in plants, farms, and distributed networks.[9]

Why NIST?

CTL possesses the capabilities to advance ultra-sensitive, quantum-enhanced molecular and atomic measurements through its leadership in frequency-comb spectroscopy, fieldable instrumentation, and traceable metrology. The Fiber Sources and Applications Group has developed portable dual-comb systems capable of kilometer-scale, open-path gas analysis with laboratory-level precision, including methane and CO_2 detection at parts-per-million sensitivity. Ongoing research in mid-infrared frequency combs and coherent dual-comb spectroscopy expands sensing into challenging spectral regions. Supported by CTL's calibration infrastructure, uncertainty analysis, and collaborative partnerships, these capabilities enable low-SWaP, turn-key systems for industrial, agricultural, and environmental monitoring across meter-to-megameter scales.

Implementation Pathways

The table below links each spectrum science 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.

Key Trends and Drivers	• Advances in Communications Architecture • Collaboration and R&D Infrastructure
Supporting Gaps	• Broadband Optical Sources and Coherent Measurement Techniques • Quantum-Limited and Quantum-Enhanced Ultra-Sensitive Detection Techniques • Field Measurements to Support Industry
Action Items	• Develop broadband, quantum-limited mid-IR and longwave-IR spectroscopic techniques • Demonstrate capabilities in real-world sensing environments • Technology transfer of critical systems to industry partners • Demonstrate networked quantum sensors over >100 km separation with femtosecond synchronization
Resource Requirements	• Staff expertise in non-linear optics and femtosecond lasers, atmospheric propagation and measurement, algorithm design for fast digital control systems and field trial experience relevant to specific sensor applications. • Field-site travel support • Additional industrial partnerships to allow access to emission sites of interest
Standards Contribution	• Provides independent verification of emerging industry measurement techniques • Provides cattle emission measurements to cattle feed suppliers, providing traceability in emission trading markets • Provides high-accuracy spectra to improve monitoring capabilities for the larger community
Success Measures (KPIs)	• Demonstrate quantum-limited broadband dual-comb in spanning the Long-Wave Infrared (LWIR) fingerprint region (6-12 um) • Establish long-term, industry-accessible monitoring sites and provide emission measurements for multiple animal feed and supplement providers • Establish new measurement capabilities for hard-to-detect trace-gas species

Goal 3: Increase Spectrum Coexistence Reliability and Performance

Coexistence of Systems: The increasing diversity of spectrum users, ranging from high-throughput broadband services to latency-sensitive IoT and radar systems, creates coexistence challenges. R&D must focus on designing coexistence protocols and frameworks that enable diverse applications to share spectrum effectively while maintaining performance, particularly in environments with mixed legacy, heterogeneous protocols, and critical systems (e.g., radar, defense, non-terrestrial systems).

Why is this a priority?

As networks push for reliable, low-latency, context-aware operation across mid- and high-band spectrum, industry needs concrete rules of engagement that ensure interoperable performance in dynamic, non-stationary environments. Data-driven, realistic models provide the evidence base to size interference margins, verify scalability, and de-risk integration before new spectrum-intensive technologies are introduced to operational network environments. In parallel, DSS demands control-plane efficiency and security in multi-user, real-time access, making clear coexistence behaviors and verification methods essential for mixed legacy, mixed licensing, radar, and non-terrestrial systems. Creating coexistence frameworks ensures that new and legacy systems can communicate smoothly, reliably, and with appropriate prioritization, protecting critical services like radar and emergency communications. Addressing this goal results in more predictable service quality in shared bands, faster certification and deployment, lower integration costs, and a stronger path to industrial competitiveness and resilience for U.S. suppliers and operators. In addition to these advances, this goal is a priority for NIST and industry as its successful implementation contributes to:

- **Ensuring Reliable Communication:** Wireless networks are becoming increasingly congested due to simultaneous usage by terrestrial, satellite, 5G, Wi-Fi, IoT, and other emerging applications. This rapid network densification and shared use among terrestrial and satellite systems are driving up interference risk and complicating inter-technology interactions, which directly threaten service reliability as bands become crowded. Addressing this requires coexistence methods that actively sense conditions and adapt channel access to maintain throughput and stability. As spectrum becomes more congested, innovative coexistence methods are necessary to ensure reliable communications while preventing service degradation.[11]
- **Establishing Protocols and Frameworks:** Centralized spectrum-management models show how clear interference-protection rules translate into dependable operations at scale. This kind of protocol-driven governance creates the stable conditions industry needs to invest and iterate on future sharing models.[12] Coexistence frameworks that coordinate

spectrum use across technologies (e.g., LTE, Wi-Fi, Bluetooth) maximize efficiency in shared and unlicensed bands and reduce hoarding by enabling concurrent operation tailored to each system's protocol.[13]

Why NIST?

CTL's status as a trusted, non-regulatory entity enables the lab to convene industry, government, and academic stakeholders across telecommunications sectors (next-generation cellular, IoT, radar, and non-terrestrial systems) to define coexistence standards and validate performance without bias, enabling the design of new coexistence frameworks for systems in shared spectrum environments. CTL's proven measurement science expertise and existing instrumentation, testbeds, evaluation frameworks, and calibration tools enable CTL staff to quickly and credibly develop repeatable test methods for evaluating how different systems interact with one another, accelerating technical innovation and regulatory adoption, supporting a wide variety of shared spectrum use cases.

Implementation Pathways

The table below links each spectrum science 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.

Key Trends and Drivers	• Advances in Communications Architecture • Dynamic Spectrum Sharing
Supporting Gaps	• Coexistence in Heterogeneous Applications • Realistic Testing Environments • Dynamic Spectrum Sharing and Cognitive Access • Interference Characterization, Impact Prediction, and Intelligent Sensing • Standardized Measurement Techniques (e.g., system-on-system coexistence testing, interference testing) • Developing Robust Measurement Methods and Data Collection Strategies • Measurement Informed Policy Development Process
Action Items	• Develop tools to evaluate spectrum sharing solutions, both simulation-based and measurement-based • Support administration priorities related to spectrum use, coexistence, and interference analyses • Increase engagement with industry and other government agencies to better position CTL on the leading edge of coexistence topics • Apply research tools and methods in the National Advanced Spectrum and Communications Test Network (NASCTN)-led test campaigns and technology development to thoughtfully improve access to the spectrum by both Federal agencies and non-federal spectrum users

Resource Requirements	• Additional staff expertise in system-level modeling and measurement • Continued presence on relevant standards committees • Increased staff expertise to further the Program for spectrum science and NASCTN
Standards Contribution	• 3GPP contributions select working groups (e.g., SA2, RAN2) • IEEE/ANSI C63 committee • IEEE 802 contributions to select working groups • Coexistence-related IEC efforts
Success Measures (KPIs)	• Tools are made publicly available and used by others • Standards are adopted and used by regulators and/or industry • Next-generation communications technology incorporates NIST output into its development and deployment

Goal 4: Develop a Harmonized Aggregate Emissions Definition

Aggregate Emissions: In concert with spectrum stakeholders, CTL will develop scientifically grounded definitions of aggregate emissions and quantities of importance, establish appropriate assumptions, and outline measurement methods to create viable estimations of aggregate emissions for use in shaping dynamic spectrum sharing and commercial and federal deployments.

Why is this a priority?

Developing scientifically grounded definitions of aggregate emissions is essential to advancing spectrum sharing in increasingly complex wireless environments.[14] Growing diversity in spectrum users increases interference risks, making reliable emissions estimates critical for coexistence frameworks and future policy development.[15] Evolving dynamic spectrum sharing approaches depend on scalable, trusted methods to quantify emissions across diverse devices and conditions, yet current capabilities remain limited.[16] Expanding cross-sector collaboration offers opportunities for aligned standards, but inconsistent definitions and measurement approaches create uncertainty for researchers, regulators, and industry stakeholders.[16] Further research is needed to establish common assumptions and scientifically defensible methods that support reliable coexistence planning and long-term spectrum access strategies. In addition to these advances, this goal is a priority for NIST and industry, as its successful implementation contributes to:

- **Policy and Regulatory Foundations:** Developing deterministic, percentile-based, and area-aware definitions of aggregate emissions is critical for ensuring that future spectrum-sharing frameworks are predictable and scalable.[1616] As deployments increase, relying on variable, device-level limits or probabilistic methods can create uncertainty and leave incumbent services vulnerable to unexpected interference.[16] Without scientifically grounded definitions that account for how emissions truly combine in dense, real-world environments, industry faces challenges in building business cases, coordinating across multiple systems, and ensuring reliable access for all users.[17]

- **Engineering and Deployment Design:** Designing future spectrum-sharing networks that can operate reliably in complex, real-world environments will depend on developing clear engineering models and assumptions that can guide deployment decisions. Variations in density, mobility, and operating conditions make it difficult to predict how signals combine without well-defined quantities like path-loss, shadowing effects, and guard distances.[18] Complex environments, such as high-density clusters, radar-sensitive areas, or highly mobile platforms like unmanned aerial vehicle (UAV) swarms, introduce unpredictable interference patterns that current models cannot fully capture.[19]
- **Measurement & Modeling Frameworks:** Reliable measurement and modeling frameworks are essential for understanding how multiple wireless systems interact in shared spectrum environments. Without clear methods linking deployment factors like device counts, duty cycles, and antenna patterns to combined emissions, interference remains challenging to predict.[18] Complex deployments highlight the need for adaptive models that account for varying densities and placements.[20] Real-world satellite-to-terrestrial studies show that small changes in device activity can significantly affect interference, underscoring the value of calibrated, repeatable estimation methods.[14] Research into sensor placement further demonstrates how monitoring design impacts accuracy, stressing the need for science-based measurement strategies.[21]

Why NIST?

CTL's commitment to traceable science qualifies the lab to develop scientifically grounded definitions and measurement methods for aggregate emissions through its expertise in spectrum metrology, advanced testbeds, and national coordination. Its Shared Spectrum and Applied Systems Metrology Groups have pioneered techniques for characterizing emissions and interference in complex radio frequency (RF) environments. As host of NASCTN, CTL brings together agencies and industry to run reproducible, scalable measurement campaigns that shape spectrum policy and coexistence frameworks. These strengths enable CTL to establish quality metrics, metadata standards, and statistical methods that support trusted aggregate emissions estimates for dynamic spectrum sharing and both commercial and federal deployments.

Implementation Pathways

The table below links each spectrum science 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.

Key Trends and Drivers	• Realistic Modeling and Validation • Collaboration and R&D Infrastructure

Supporting Gaps	• Propagation Prediction • Establish Trust in Spectrum Data • Standardized Measurement Techniques • Interference Characterization, Impact Prediction, and Intelligent Sensing • Aggregate Interference
Action Items	• Engage with the federal and industry to identify relevant areas of concern • Develop measurement methods for Aggregate Emissions • Develop data dissemination frameworks
Resource Requirements	• Staff expertise in radio propagation modeling, physics, and measurements • Expertise in data frameworks
Standards Contribution	• Enable Federal stakeholders to engage on Standards with NIST data and methods • Develop a NIST-led lexicon of definitions for aggregate emissions
Success Measures (KPIs)	• Adopt NIST measurement methods and data • Increase regulatory actions citing NIST • Monitor Federal Agency recommendations based on NIST data

Goal 5: Define Standards for Spectrum and Environment Sensing

Spectrum and Environment Sensing: CTL will establish the essential features of spectrum data products containing measured or modeled spectrum data that incorporate scientific measurement or modeling methods, expectations for data quality, and well-founded statistical analyses.

Why is this a priority?

Establishing the essential features of spectrum data products, including standardized fields, traceable provenance, quality metrics, and statistical confidence, directly links three key drivers to industry outcomes. Data sharing and reproducibility enable standard schemas and metadata that make results comparable across labs and vendors, building trust with regulators and customers and shortening certification and procurement cycles. Realistic modeling and validation depend on calibrated, measured, and modeled data to tune interference and propagation models and to verify coexistence performance under dense, dynamic conditions, reducing integration risk before deployment. AI/ML and agile testing environments require well-labeled, reproducible datasets with clear uncertainty measures to automate testing, speed iteration in testbeds, and scale validation across devices and bands. Addressing this goal improves time-to-market, interoperability, and spectrum efficiency while mitigating risk to investments in NextG products and services. In addition to these advances, this goal is a priority for NIST and industry as its successful implementation contributes to:

- **Enhancing Decision-Making:** Establishing essential features for spectrum data products provides a standardized foundation for decision-making in spectrum sharing environments. Testbed-driven solutions depend on comparable, trusted data collected using consistent methods.[22] Without standardization, automated identification of spectrum reuse opportunities through Spectrum Consumption Models (SCMs) becomes unreliable, leading to inefficiencies in real-time coordination.[23] Machine-readable models enable policies to be applied consistently across automated systems, avoiding subjective interpretations of harmful interference and enabling confident, timely deployment decisions.[23]
- **Facilitating Large-Scale Monitoring:** Industry planning for future spectrum access depends on scalable, cost-effective monitoring solutions. Large-scale, crowdsourced sensing relies on data products that include time, location, frequency granularity, and confidence parameters, allowing industry to characterize usage patterns over space and time reliably.[24] Well-defined features for spectrum data products ensure that inputs from varied monitoring sources read consistently, supporting industry investments in dynamic spectrum sharing while enabling regulators to track compliance and optimize allocations in real time.
- **Scalable and Cost-Effective Monitoring:** Standardized spectrum data products make large area monitoring practical by matching low-cost, low-power sensors with data fields that industry can aggregate at scale. Widespread spectrum monitoring depends on many distributed sensors and a processing backbone to learn, detect, and predict occupancy, enabling data-driven sharing decisions rather than one-off measurements.[24]

Why NIST?

CTL's expertise in spectrum metrology, advanced calibration services, and validated measurement methods provide a strong basis to define the essential features of spectrum data products. The Spectrum Technology and Research Division develops scalable, trusted techniques for generating high-quality data across diverse RF environments, while NASCTN convenes federal, industry, and academic partners to conduct reproducible, scientifically rigorous measurement campaigns. These capabilities ensure traceability to SI units, robust uncertainty analysis, and consistent data quality standards to support dynamic spectrum sharing across commercial and federal domains.

Implementation Pathways

The table below links each spectrum science 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.

Key Trends and Drivers	• Realistic Modeling and Validation • Data Sharing and Reproducibility

	• Artificial Intelligence (AI), Machine Learning (ML), and Agile Testing Environments
Supporting Gaps	• Establish Trust in Spectrum Data • Standardized Measurement Techniques • Interference Characterization, Impact Prediction, and Intelligent Sensing
Action Items	• Disseminate and solicit feedback on guidelines for tiers of spectrum measurement quality • Develop guidelines and tools for spectrum measurement methods • Publish high-quality datasets • Develop data analysis methods • Apply research tools and methods in NASCTN led test campaigns and technology development to thoughtfully improve access to the spectrum by both Federal agencies and non-federal spectrum users.
Resource Requirements	• Expertise in radio spectrum measurements • Expertise in data analysis • Expertise in software development and RF hardware • Staff expertise to further the Program for spectrum science and NASCTN
Standards Contribution	• Enable Federal stakeholders to engage on Standards with NIST data quality guidelines • Increase NIST publications on measurement and data guidelines for standards engagements by U.S.-led interests
Success Measures (KPIs)	• External Adoption of NIST measurement methods and data structures • Increase regulatory actions citing NIST methods and results • Monitor Federal Agency recommendations based on NIST data

Roadmap Impact

The Spectrum Science Roadmap positions CTL to drive for American leadership in spectrum science by aligning technical research with public priorities, policy needs, and industry requirements. By defining measurable goals, identifying critical gaps, and linking both to resource planning, the roadmap ensures that future CTL efforts focused on spectrum science research and its applications produce credible, high-impact results. The roadmap's influence extends beyond internal planning; it informs U.S. standards positions, supports regulatory innovation, enables industry adoption of dynamic spectrum technologies, and fosters adoption across the national research ecosystem.

Together, these outcomes reflect CTL's unique ability to deliver trusted science in service of national goals and global competitiveness by:

Reinforcing U.S. Leadership in Spectrum Policy and Standards

The priority research initiatives described in this roadmap strengthen the United States' global leadership in spectrum policy and standards by aligning CTL's measurement science expertise with the nation's strategic spectrum objectives, including development of novel test methods, modeling and simulation capabilities, and analysis insights to allow Federal entities with equities and stakeholders in the bands to inform on needs for band reallocation and valuation, as codified in *Public Law No. 119-21*.[25] By contributing rigorous technical data, metrology frameworks, and methodologies that lead towards standardization, CTL reinforces the integrity of U.S. positions in international forums and collaborative standards development processes. Through stakeholder engagement and coordination with federal agencies, the roadmap ensures that CTL's work directly informs policy decisions and provides a credible scientific foundation for U.S. leadership in spectrum governance.

Enhancing Trust in Dynamic Spectrum Technologies

The CTL R&D goals described in this roadmap enhance trust in dynamic spectrum technologies by establishing transparent, scientific test methodologies for performance characteristics, interference assessment, and environmental sensing. These goals support the development of testbeds, trusted datasets, validation tools, and best practices that enable predictable and secure operation in shared spectrum environments and increase cross-sector engagement on topics of coexistence. CTL's work fosters industry and stakeholder confidence in adopting dynamic spectrum access approaches as scalable, dependable solutions by reducing uncertainty and demonstrating capability through rigorous measurement and modeling.

Aligning with National Priorities

By strategically aligning CTL's research activities with national spectrum priorities, including spectrum usage assessment and band analyses, CTL ensures targeted investment in high public value areas. Early engagements with national spectrum priority area working groups identifies unique opportunities where CTL's metrology expertise complements ongoing work across government, academia, and industry, fostering collaboration and strengthening science and allows CTL to demonstrate core capabilities in relevant applications. This alignment not only improves operational efficiency and resource utilization but also exercises CTL's distinctive role within the national research ecosystem, enabling opportunities to demonstrate focused and impactful research agenda.

Supporting Industry Adoption

CTL spectrum science priorities described in this roadmap support industry adoption of efficient, shared-spectrum solutions by bridging the gap between emerging technology needs and the measurement science required for deployment at scale. By addressing stakeholder needs through informed goal setting in designing coexistence protocols, improving the applicability of dual-comb spectroscopy, and establishing expectations for data quality, CTL accelerates the development of standards and validation methods necessary for commercial rollout. CTL's work provides industry with the tools, benchmarks, and confidence needed to invest in and adopt spectrum sharing technologies, driving innovation and more effective use of limited spectrum resources.

Conclusion/Ending Remarks

This roadmap goal is to establish clear, actionable pathways for advancing spectrum science research aligned with national priorities, stakeholder needs, and CTL's core capabilities. The output of this document is based on rigorous analysis, cross-sector engagement, and strategic goal setting to map CTL's resources to the most impactful challenges in measurement science, coexistence, and spectrum innovation. By connecting research goals to validated gaps and implementation pathways, CTL positions itself to capitalize on its strategic position and challenges to lead with purpose, towards achievable five to seven-year objectives.

The appendices that follow provide additional details on the collaborative process, subject matter experts, and reference materials that shaped this roadmap and may be drawn upon to continue to guide its execution.

Appendix A: Detailed Gaps List

In partnership with external stakeholders and internal SMEs, CTL drafted the following gaps in addition to the gaps listed in the Spectrum Science Gaps section earlier in the roadmap. CTL determined that the gaps below were not high priority, could not be accomplished in the next five-to-seven-year time frame, or were out of scope for CTL or the specific area of spectrum science. Elements outside of the scope of spectrum science but within nominal acceptance criteria are intended to be moved to a different roadmap topic area. While these gaps are not actionable at this time, their inclusion in the roadmap provides additional context to the broad discussions and depth of analysis conducted on spectrum science research and technology needs. Though some of these gaps may not be actionable today, they are monitored and revisited as a part of CTL's annual project planning process.

Additional Gaps Discussed

Spectrum Sharing

Compressed Operating Environments: Spectrum sharing poses significant challenges in electromagnetically dense and physically constrained environments, such as urban centers, industrial facilities, and mobile platforms. DSS systems must address high user densities, limited available bandwidth, and environmental restrictions that complicate in situ spectrum use.

Real-Time Spectrum Sharing Efficiency: To be effective, Spectrum-sharing approaches need to adapt to changing demands, ideally in real-time. There is a critical need for R&D on real-time, adaptive spectrum-sharing algorithms that can dynamically allocate resources in spectrum-dense, high-demand environments.

Measurements that Support the Ability to Determine Interference

Defining and Detecting Full-Spectrum Occupancy: There is a lack of clear definitions and reliable methods for determining when a given spectrum band or geographic area is truly "fully occupied." This need includes identifying the thresholds and conditions that signify maximum utilization and prevent further efficient allocation.

Hardware Enhancements

Adaptive Beamforming: To ensure the effectiveness of passive users and specific geographic location needs, NIST should spearhead research and development in advanced, fine-grained beamforming and interference avoidance. Industry-driven adaptive beamforming development may not adequately prioritize these particular requirements. Potential research areas include sophisticated beamforming techniques for non-terrestrial networks, extending beyond basic spot beams, to enable precise geofencing. This research would protect both active and passive terrestrial incumbents. For instance, spot beam synthesis could be augmented (and intentionally distorted) by applying geographically anchored null beam constraints towards protected radio astronomy and sensitive government sites.

Distributed and Cooperative Antenna Beamforming: Most antenna beamforming systems operate independently. There is potential for significant improvement by enabling cooperation between multiple antenna front ends. Research should focus on developing distributed and cooperative antenna beamforming techniques where various systems share antenna information and coordinate their beam patterns to minimize overall interference and optimize communications operations across a wider area. This research could involve developing distributed low-computational cost algorithms, communication protocols for antenna coordination, and mechanisms for secure information sharing.

Adaptive Signal Processing: Existing receiver designs and signal processing techniques often lack the agility to adapt to rapidly changing interference. Research is needed to develop adaptive filters, interference cancellation algorithms, and hardware components (e.g., reconfigurable RF front ends) that can dynamically adjust their parameters based on real-time interference characterization. This research includes exploring machine learning-based approaches for interference prediction and mitigation.

Optical communication, sensing, and spectroscopy

Clock Packaging: There is a need to develop compact, low-SWaP (Size, Weight, and Power) fiber-based clocks locked to atomic or other fundamental transitions for precise timekeeping. While these systems offer exceptional stability and performance, their current packaging and deployment limitations hinder scalability for ground-based and spaceborne applications. Miniaturization, environmental shielding, and integration with existing infrastructure require further development. Addressing this would enable robust, distributed time synchronization across critical systems like satellite constellations and quantum networks.

Near and Mid-Infrared Optical Sources, Coherent Measurement Techniques, and Broadband Infrared Sources: There is a need to detect low-level concentrations of chemical and biological substances, hindered by limitations in both wavelength coverage and high signal-to-noise detection methods. Key challenges include limited infrared spectral coverage, inadequate device SWaP, and the need for more sensitive and coherent measurement techniques. Existing infrared sources often fall short in wavelength range, restricting the ability to detect substances with diverse absorption properties. Research should prioritize developing broadband infrared sources such as supercontinuum lasers or tunable quantum cascade lasers that can span a wider spectral range. This expanded coverage would allow for the simultaneous detection of multiple substances and enhance the flexibility and performance of sensing systems.

Ultra-Sensitive Detection Techniques: Detecting low concentrations of substances requires highly sensitive detection methods that can effectively extract weak signals from noisy backgrounds. Research should focus on developing ultra-sensitive detection techniques, such as cavity-enhanced spectroscopy, photoacoustic spectroscopy, or heterodyne detection. These techniques can significantly improve the signal-to-noise ratio and enable the detection of trace amounts of substances in complex environments.

Sensing, Monitoring, and Control

Spectrum Monitoring at Scale: Existing spectrum monitoring systems often struggle to scale to dense and dynamic spectrum environments, which need a massive number of devices and signals monitored in real-time. This need is both a simulation and a hardware challenge. Modeling and simulation need to address the topology and size of a distributed sensing network. In contrast, the spectrum monitoring system implementation needs to focus on scalability and efficiency in collecting and processing large volumes of spectrum data from diverse sources. This could involve leveraging edge computing, heterogeneous proliferated sensing architectures, and crowdsourced sensing techniques.

Safe Sharing of Sensitive Information: Sharing spectrum while protecting privacy and proprietary data is essential but requires new approaches to security and privacy. Innovative techniques for secure spectrum sharing are needed to protect sensitive information from unauthorized access and eavesdropping. This process could involve developing encryption techniques, privacy-preserving data sharing protocols, and differential privacy mechanisms.

Spectrum System Security: Spectrum-dependent systems are vulnerable to various security threats, including jamming, spoofing, and denial-of-service attacks. Robust security mechanisms are needed to protect spectrum systems from malicious disruptions and cyberattacks. This process could involve developing intrusion detection systems, anti-jamming techniques, and secure authentication protocols.

Optical Communication, Sensing, and Spectroscopy

Miniaturized and Low-Power Devices: Current infrared sensing systems often involve bulky and power-hungry components, limiting their portability and practical field use. Research should focus on developing miniaturized and low-power infrared sources and detectors, potentially leveraging integrated photonics or micro-electromechanical systems (MEMS) technologies. This miniaturization would enable compact and portable sensing devices suitable for field applications and remote deployments.

Non-R&D Gaps

Collaboration Barriers Due to Industry Competition
Competitive pressures between industries often discourage collaboration and information sharing, creating silos that hinder progress in spectrum science. This distinguisher makes NIST uniquely positioned to lead pre-competitive research efforts. Research should focus on establishing neutral, collaborative frameworks that facilitate data sharing and joint innovation across sectors without compromising competitive advantages. NIST's role as a trusted intermediary can help foster partnerships, align stakeholder priorities, and create a shared repository of knowledge to advance spectrum-sharing technologies.

Economic Feasibility for Industry-Led Spectrum Research
The high cost and uncertain returns on investment for spectrum-sharing R&D make it challenging for industries to allocate resources and assume risks. Many organizations lack the financial and technical capacity to engage in long-term, high-risk research. Addressing this gap requires the development of incentive models, public-private partnerships, and funding mechanisms that encourage industry participation while reducing financial and operational risks. Demonstrating the long-term economic benefits of spectrum-sharing innovations will be critical to overcoming this barrier.

Gaps Moved to Other Roadmaps

Space 2.0 EMI/EMC: Reducing Barriers to Entry for Small Startups: The increasing accessibility of space through initiatives like Space 2.0 presents a growing risk of difficult-to-resolve EMI issues from large satellite constellations. A key challenge is the high cost associated with comprehensive EMI testing, creating a significant barrier to entry for small startups. While discussions have highlighted the need for developing best measurement practices to drive mandatory broad-spectrum EMI standards for satellites, the immediate concern for the EMI/Electromagnetic Compatibility (EMC) community in the space sector is often self-compatibility within satellites themselves. Interference can arise not just from intentional transmitters but also from ancillary electronics. System operators frequently cite the expense of thorough, broad-spectrum EMI evaluations before launch. However, the inability to rectify EMI problems once a satellite is in orbit underscores the critical need for accessible and cost-effective EMI testing solutions. Addressing this gap is essential to ensure responsible spectrum management and mitigate potential interference in the evolving space environment.

Field Measurements and Models for Active-Passive Channel and Real-time Adaptive Antenna Beamforming: To establish effective service rules, such as out-of-band emission (OOBE) limits, that protect passive remote sensing bands from active transmitters, regulators urgently require accurate, measurement-validated models of skyward scattering of horizontal radiation, particularly in millimeter-wave bands. Regulators should integrate this into the spectrum sensing program by combining efforts in field measurements and model development for active-passive channel characterization.

Accurate Channel Modeling for Space-Air-Ground Communications: Existing channel models for ground-to-satellite and satellite-to-ground links lack accuracy in accounting for real-world propagation characteristics. This gap includes atmospheric attenuation, multipath effects, rain fade, and Doppler shifts, particularly at higher frequency bands like mmWave, Ka-band, and THz.

Real-time Adaptive Antenna Beamforming: Existing antenna beamforming techniques often struggle to adapt quickly enough to the dynamic nature of interference and mobile users in real-time. Research should focus on developing real-time adaptive beamforming algorithms that can dynamically adjust beam patterns in milliseconds to effectively mitigate interference and maintain reliable communication links in rapidly changing environments. This research could involve leveraging advanced signal processing techniques, machine learning, and real-time feedback from spectrum sensors. In its advanced form, this could also include algorithms, computed at the edge, that predict the optimum beamforming based on anticipated conditions.

Appendix B: Existing Projects and Current Capabilities

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

Adaptive Closed-Box Interference Susceptibility Testing

This project aims to move beyond traditional steady-state testing by developing methods to assess how COTS communication systems respond to complex and dynamic spectrum environments. The goal is to better understand and improve system resilience to interference.

CBRS Sharing Ecosystem Assessment

This NASCTN project collects data to evaluate the effectiveness of the Citizens Broadband Radio Service (CBRS) sharing ecosystem, particularly how Spectrum Access Systems and Environmental

Sensing Capabilities manage coexistence between commercial and Department of Defense systems. The five-year study provides insights into the effectiveness of spectrum sharing and tracks environmental changes over time.

Fiber Sources and Applications: Background Information

NIST is developing optical frequency comb technology that transforms single-frequency laser sources into pulses containing thousands of frequencies. This advancement supports applications such as high-speed infrared spectroscopy and enhanced telecommunications signal assessments.

Fiber-optic Frequency Comb Development

This project focuses on creating robust, high-performance frequency combs based on fiber-optic technology suitable for field applications. These combs are essential for various uses, including laser ranging, precision spectroscopy, optical timing distribution, and supporting optical clocks.

Frequency-comb-based Spectroscopy (Dual-Comb Spectroscopy)

NIST is advancing dual-comb spectroscopy, a technique that leverages the coherence and accuracy of frequency combs for precision molecular spectroscopy. This method enables high-resolution, accurate measurements in both laboratory and field settings.

METIS: A Metrology Exchange to Innovate Semiconductors

METIS, Metrology Exchange to Innovate Semiconductors, serves as a platform to provide stakeholders with access to CHIPS Metrology research results, aiming to catalyze innovative breakthroughs in U.S. semiconductor manufacturing. The beta version includes data from initial projects focusing on high-speed metrology, multiscale modeling, and calibration networks.

RF Metrology for High-Frequency Transistor Models

This project seeks to enhance the modeling, design, and fabrication of high-frequency circuits by analyzing the predictive performance of existing models. It incorporates fabrication process variations into model responses and validates models on actual circuits to improve accuracy and reproducibility.

Miniaturized Microwave Absolute Calibration

A collaboration among NIST, Colorado State University, Duke University, and Northrop Grumman, this project aims to improve remote-sensing calibration standards for small satellites. The goal is to enhance instrument evaluation, increase data repeatability, and enable effective calibration and traceability among satellite microwave instruments.

Open RAN Research at NIST

NIST is supporting the development of next-generation Open Radio Access Networks (Open RANs) characterized by disaggregated network elements and intelligent controllers. By developing standardized interfaces and testing methodologies, NIST aims to facilitate the seamless integration of components from different vendors and to enhance the performance assessment of Open RAN solutions.

Optical Two-way Time-frequency Transfer

This project develops techniques for precise time-frequency transfer across free-space links to support future optical clock networks. The method enables synchronization between distant clocks to within femtoseconds, even in turbulent or rapidly changing environments.

Thermal Noise Metrology

NIST is working on methods to accurately measure thermal noise, which is fundamental in quantum measurement systems. This research supports the development of ultra-sensitive measurement techniques necessary for advanced scientific applications.

Trusted Spectrum Testing

This project aims to develop testing methodologies to assess and ensure the trustworthiness of spectrum usage. It includes evaluations of aggregate emissions from various systems to support reliable and secure spectrum sharing.

Wireless Coexistence

NIST addresses challenges related to the coexistence of wireless systems by developing standards and test methods. The goal is to ensure reliable operation of multiple wireless systems within shared spectrum environments.

Assessment of Current Capabilities

This assessment of CTL's current capabilities and technical strengths draws from stakeholder interviews, internal reviews, and relevant literature and guides the prioritization of R&D goals and resource investments. It ensures that future efforts build strategically on CTL's core competencies while addressing critical technology gaps.

Current Capabilities

Neutrality and Trust

NIST is a neutral party with objective scientific expertise, providing spectrum science standards and best practices to advance industry innovation and competitiveness on the global market. NIST does not compete with industry or academia; the institute develops measurements and standards to benefit American industrial competitiveness. NIST's neutrality fosters trust with industry stakeholders, enabling open collaboration and serving as a reliable partner in advancing spectrum science and technology development. By providing traceable measurements, NIST continues to strengthen its relationships with industry and government partners, answering crucial metrology questions in spectrum science to assist in the use of the radio spectrum. While it may not make economic sense for industry or academia to address some problems within spectrum science, the insulation of NIST from market pressures provides a perfect setting for advancing measurement science in this area, including understanding the behavior of spectrum systems and ecosystems for optimization. NIST researchers have the flexibility to pursue innovative projects and explore experimental solutions that may be beyond the scope of industry and academic research, driving breakthrough advancements in spectrum science.

Expertise in Radio Frequency Engineering and Spectrum Science

NIST possesses deep expertise in understanding radio frequency systems in the context of their use and impact on the spectrum. This expertise includes end-to-end system characterization, communications protocols, modeling and simulation, backed by testing and published methods in measurement and modeling. This capability supports critical advancements towards standardization in coexistence, spectrum sharing, and interference modeling. The involvement by NIST in cutting-edge projects, such as 6G, 4D spectrum sharing, Non-Terrestrial Networks, spectrum sharing management, defining spectrum sharing frameworks, and contributions to standards like 3GPP 4G and 5G New Radio (NR), highlights its broad capabilities and leadership in wireless communications research and development.

Facilities and Measurement Capabilities

NIST's state-of-the-art facilities and advanced measurement capabilities allow for the deployment and characterization of large-scale wireless systems. In addition to multiple testbeds, including the CTL innovation network, 5G Coexistence Testbed, National Broadband Interoperability testbed, and the 5G/6G Networks Testbed, NIST also houses the Robotically Enhanced Antenna Laboratory for Metrology (REALM), which facilitates highly accurate and precise antenna calibrations. These cutting-edge facilities make NIST a desired partner for both industry and government for testing and validation across the full communications stack.

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
Anne Lane	CTL Chief of Staff
Jason Coder	Spectrum Technology and Research Division (675)
Richard Rouil	Wireless Networks Division (673)

Chris Carson	CTL Administrative Specialist
Ian Coddington	Spectrum Technology and Research Division (675)
Kevin Cossel	Spectrum Technology and Research Division (675)
Nada Golmie	NIST Fellow
David Griffith	Wireless Networks Division (673)
Yao Ma	Spectrum Technology and Research Division (675)
Duncan McGillivray	Spectrum Technology and Research Division (675)
Melissa Midzor	Previous CTL Director
Susanna Mosleh	Spectrum Technology and Research Division (675)
Thao Nguyen	Wireless Networks Division (673)
Jeanne Quimby	Spectrum Technology and Research Division (675)
Anirudha Sahoo	Wireless Networks Division (673)
Brian Washburn	Spectrum Technology and Research Division (675)
Adam Wunderlich	Spectrum Technology and Research Division (675)
David Goldstein	NTIA
Nickolas LaSorte	NTIA
Dan Marrone	The University of Arizona
Eric Nelson	NTIA
Scott Paine	Harvard
Rick Reaser	SpectrumX
Tom Taylor	MITRE

Appendix D: Works Cited

The roadmap utilized the following sources while developing this Spectrum Science Roadmap to ensure technical accuracy, alignment with national priorities, and incorporation of stakeholder perspectives. These materials include federal legislation, agency publications, and expert-led research that collectively inform the roadmap's research goals and implementation frameworks.

[1] Seda Doğan-Tusha, Armed Tusha, Muhammad Iqbal Rochman, & Monisha Ghosh (2025, February). *Spectrum Sharing Characterization Using Smartphones: Exploring 6 GHz Sharing Through Large-Scale Wi-Fi 6E Measurements*. IEEE Communications Magazine. Retrieved from https://doi.org/10.1109/MCOM.001.2400325

[2] Next G Alliance Spectrum Working Group (2024–2025). *Spectrum Needs for 6G*. Next G Alliance white paper. Retrieved from https://nextgalliance.org/white_papers/spectrum-needs-for-6g/

[3] Purva Rajkotia (2025, January 15). *Six Connectivity and Telecom Trends to Watch for in 2025*. IEEE Standards Association, Beyond Standards. Retrieved from https://standards.ieee.org/beyond-standards/2025-connectivity-telecom-trends/

[4] Nada Golmie, Alhussein A. Abouzeid, Thyagarajan Nandagopal, Murat Torlak, Marc Leh, Miller Higgins (2023) *NextG Communications Research and Development Gaps Report*. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 1293. https://doi.org/10.6028/NIST.SP.1293

[5] Hossein Nasiri, Seda Dogan-Tusha, M. I. Rochman, Monisha Ghosh (2024) *Data Driven Environment Classification Using Wireless Signals.* The 30th Annual International Conference on Mobile Computing and Networking (ACM MobiCom '24), Washington D.C., DC, USA. ACM, New York, NY, USA. https://doi.org/10.1145/3636534.3697319

[6] Thomas W. Hazlett, Dongning Guo, Michael Honig (2023) *From "Open Skies" to Traffic Jams in 12 GHz: A Short History of Satellite Radio Spectrum*. Journal of Law & Innovation, Vol. 6, No. 1, November 2023. https://journaloflawinnovation.org/article/view/7312/5913

[7] Hugo Bergeron, Laura C. Sinclair, William C. Swann, Isaac Khader, Kevin C. Cossel, Michael Cermak, Jean-Daniel Deschênes, and Nathan R. Newbury (2019). *Femtosecond Time Synchronization of Optical Clocks Off of a Flying Quadcopter*. Nature Communications, 10:1819. Retrieved from https://doi.org/10.1038/s41467-019-09768-9

[8] Scott E. Crawford, Roman A. Shugayev, Hari P. Paudel, Ping Lu, Madhava Syamlal, Paul R. Ohodnicki, Benjamin Chorpening, Randall Gentry, and Yuhua Duan (2021). *Quantum Sensing for Energy Applications: Review and Perspective*. Advanced Quantum Technologies, 4(8), 2100049. Retrieved from https://doi.org/10.1002/qute.202100049

[9] Ang Li, Chunhui Yao, Junfei Xia, Huijie Wang, Qixiang Cheng, Richard Penty, Yeshaiahu Fainman, & Shilong Pan (2022, May 15). *Advances in cost-effective integrated spectrometers. Light: Science & Applications.* Nature Publishing Group. Retrieved from https://doi.org/10.1038/s41377-022-00853-1

[10] Jingjun Wu, Cong Wei, Hanxiao Cui, Fujia Chen, Kang Hu, Ang Li, Shilong Pan, Yihao Yang, Jun Ma, Zongyin Yang, Wanguo Zheng, & Rihong Zhu (2024, November 26). *High-Sensitivity, High-Resolution Miniaturized Spectrometers for Ultraviolet to Near-Infrared Using Guided-Mode Resonance Filters.* Molecules, MDPI. Retrieved from https://doi.org/10.3390/molecules29235580

[11] Nagma Parveen, Khaizuran Abdullah, Khairayu Badron, Yasir Javed, & Zafar Iqbal Khan (2025, April 1). *Coexistence in Wireless Networks: Challenges and Opportunities.* Telecom 2025, 6(2), 23. MDPI. Retrieved from https://doi.org/10.3390/telecom6020023

[12] Wilfried Wilde, Andrew Clegg, Preston Marshall, Kurtis Heimerl, & Sachin Katti (2022, June). *Recommendations to the Federal Communications Commission Based on Lessons Learned from CBRS.* Proceedings of the 18th USENIX Symposium on Networked Systems Design and Implementation. Retrieved from https://www.usenix.org/conference/nsdi21/presentation/wilde

[13] Susannah Mosleh, Yao Ma, Jacob Rezac, Jason Coder (2020). *Dynamic Spectrum Access with Reinforcement Learning for Unlicensed Access in 5G and Beyond*. IEEE 91st Vehicular Technology Conference. Retrieved from 10.1109/VTC2020-Spring48590.2020.9129381

[14] K.J. Zdunek, A. Wilson, & B. Passwaiter (2018, October). *Measurements and Analysis of Aggregate Interference in Satellite-Terrestrial Spectrum Sharing*. 2018 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN). IEEE Xplore. Retrieved from https://ieeexplore.ieee.org/document/8636967

[15] Miurel Tercero, Ki Won Sung, & Jens Zander (2011, March). *Impact of Aggregate Interference on Meteorological Radar from Secondary Users.* IEEE WCNC 2011 - Services and Applications. IEEE Xplore. Retrieved from https://ieeexplore.ieee.org/document/5779361

[16] Thao T. Nguyen & Michael R. Souryal (2021). *Deterministic Move Lists for Federal Incumbent Protection in the CBRS Band*. IEEE Transactions on Cognitive Communications and Networking, Vol. 7, No. 3. IEEE Xplore. Retrieved from https://ieeexplore.ieee.org/document/3030643

[17] Kate Harrison & Anant Sahai (2011, May). *Potential Collapse of Whitespaces and the Prospect for a Universal Power Rule*. 2011 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN). IEEE Xplore. Retrieved from https://ieeexplore.ieee.org/document/5936222

[18] Ki Won Sung, Miurel Tercero, & Jens Zander (2011, June). *Aggregate Interference in Secondary Access with Interference Protection*. IEEE Communications Letters, Vol. 15, No. 6. IEEE Xplore. Retrieved from https://ieeexplore.ieee.org/document/110272

[19] Jiangqi Hu, Sabarish Krishna Moorthy, Ankush Harindranath, Zhaoxi Zhang, Zhiyuan Zhao, Nicholas Mastronarde, Elizabeth Serena Bentley, Scott Pudlewski, & Zhangyu Guan (2023, December 19). *A Mobility-Resilient Spectrum Sharing Framework for Operating Wireless UAVs in the 6 GHz Band*. IEEE/ACM Transactions on Networking, Vol. 31, No. 6. Retrieved from https://doi.org/10.1109/TNET.2023.3274354

[20] Youping Zhao, Lu Shi, Xin Guo, & Chen Sun (2018, October). *Aggregate Interference Prediction Based on Back-Propagation Neural Network*. 2018 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN). IEEE Xplore. Retrieved from https://ieeexplore.ieee.org/document/8636925

[21] Joseph R. Mruk, Thao T. Nguyen, M. Keith Forsyth, Duncan A. McGillivray, & Daniel G. Kuester (2025). *Spectrum Monitoring System Deployment Site Analysis Using Realistic Radiation Patterns.* IEEE Xplore. Retrieved from https://ieeexplore.ieee.org/document/10592682

[22] Melissa Midzor (2022, May 16). *Spectrum Sharing: Implications for the Testbed Community. National Institute of Standards and Technology (NIST),* IEEE ICC 2022 Workshop on Spectrum Sharing. Retrieved from https://www.nist.gov/spectrum-sharing-testbeds

[23] Carlos E. Caicedo Bastidas & John A. Stine (2018, November). *The IEEE 1900.5.2 Standard for Modeling Spectrum Consumption*. The MITRE Corporation & Syracuse University. Retrieved from https://standards.ieee.org/1900-5-2-spectrum-consumption

[24] Nick Laneman (2022, May 16). *Teaming Up to Advance Monitoring and Sharing of the Radio Frequency Spectrum*. IEEE ICC Workshop on Spectrum Sharing Technology for Next-Generation Communications, University of Notre Dame. Retrieved from https://ieee-icc.org/workshops/spectrum-sharing-2022

[25] U.S. House of Representatives (2025) *The One Big Beautiful Bill Act*. (U.S. Congress, Washington, DC), H.R. 1, 119th Congress. https://www.congress.gov/bill/119th-congress/house-bill/1/text