National Spectrum Research and Development Plan

A Report By

WIRELESS SPECTRUM RESEARCH AND DEVELOPMENT
INTERAGENCY WORKING GROUP

NETWORKING AND INFORMATION TECHNOLOGY RESEARCH AND
DEVELOPMENT SUBCOMMITTEE

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

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The Wireless Spectrum R&D (WSRD) Interagency Working Group (IWG) coordinates federal spectrum-related R&D activities to facilitate efficient, effective R&D investments that promote efficient use of wireless spectrum through advanced technologies and systems. This vital work promotes U.S. leadership and global competitiveness in wireless spectrum R&D and its applications. The WSRD IWG reports investments to the Advanced Communications Networks and Systems Program Component Area of NITRD. https://www.nitrd.gov/coordination-areas/wsrd/

About This Document

This National Spectrum Research and Development Plan identifies key innovation areas for spectrum research as directed under Pillar 3 of the National Spectrum Strategy (NSS - November 2023): "Unprecedented Spectrum Innovation, Access, and Management through Technology Development" objective 3.2: "Commit to improving collective understanding of the electromagnetic spectrum through coordinated, focused, and sophisticated research and development (R&D)". This Plan reflects recommendations from federal stakeholders and responses from industry, academia and the public to a Request for Information published in February 2024. This Plan was informed by public input from U.S. universities, companies and industry trade organizations submitted in response to a public Request for Information. Federal agency inputs were gathered through the WSRD IWG of the National Information Technology R&D (NITRD) Program. This Plan will be revised and updated on a periodic basis. Revisions to this Plan will include stakeholder consultation via the collaborative framework mandated by the National Spectrum Strategy.
https://www.whitehouse.gov/wp-content/uploads/2023/11/National-Spectrum-Strategy.pdf

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Executive Summary

President Biden has called radio frequency spectrum one of our nation's most important national resources. On November 13, 2023, he released the Memorandum on Modernizing United States Spectrum Policy and Establishing a National Spectrum Strategy that provides orders for the heads of executive departments and agencies related to spectrum policy. On the same date, the White House released the National Spectrum Strategy, which directed the White House Office of Science and Technology Policy to develop a National Spectrum Research and Development Plan.

This Plan guides government support for spectrum-related research, helping to shape private-sector efforts, and providing a shared reference for stakeholder interactions. The goal is to continue U.S. leadership in spectrum research and development. This Plan does not direct actions or commit future resource investments by any branch of the federal government. Implementation of the recommendations in this Plan depends on decisions made in future federal budget processes.

This Plan identifies key opportunities for spectrum-related research and development. Thirteen opportunities were identified as the highest priority.

Highest priority innovation areas for use-inspired research:

- Interference and Noise Resilience
- Interference Impact Prediction
- Sharing with Critical Systems
- Regulatory Options
- Advanced Spectrum Management Processes

Highest priority innovation areas for fundamental research:

- Agile Front Ends and Antennas
- Spectrum Utilization Optimization
- Undesired Signal Prediction
- Spectrum Sharing Control
- Cost of Interference

Highest priority research accelerators:

- Public Datasets
- Testbeds and Testing Frameworks
- Spectrum Technology Readiness Level (TRL) Pipeline Review

Highest priority organizational improvements:

- Researcher Rotations into Regulatory Organizations
- Focused Research to Inform Regulatory Decisions
- Band Studies as Transition Opportunities
- Spectrum Engineering Task Force

The *National Spectrum Strategy* identified Dynamic Spectrum Sharing as a critical approach to meet the growing demand for spectrum access. Most of the innovation areas described in this Plan contribute to advancing Dynamic Spectrum Sharing.

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Abbreviations and Acronyms

3GPP	3rd Generation Partnership Project
API	Application Programming Interface
AI	Artificial Intelligence
AI/ML	Artificial Intelligence/Machine Learning
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
DSS	Dynamic Spectrum Sharing
FCC	Federal Communications Commission
GIS	Geographic Information System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union
IWG	Interagency Working Group
ML	Machine Learning
NSS	National Spectrum Strategy
NASCTN	National Advanced Spectrum and Communications Test Network
NCO	National Coordination Office
NIST	National Institute of Standards and Technology
NITRD	Networking and Information Technology Research and Development
NSF	U.S. National Science Foundation
NSTC	National Science and Technology Council
NTIA	National Telecommunications and Information Administration
OSTP	Office of Science and Technology Policy
R&D	Research and Development
RF	Radio Frequency
RFI	Request For Information
TRL	Technology Readiness Level
WSRD	Wireless Spectrum Research & Development

Part 1: Introduction

This **National Spectrum Research and Development Plan** responds to guidance established in the 2023 National Spectrum Strategy and the 2024 National Spectrum Strategy Implementation Plan (see Spotlight 1.1). In this context, the word "spectrum" refers to the radio frequency portion of the electromagnetic spectrum.

The introduction of the 2023 National Spectrum Strategy defines the broad national goals toward which spectrum R&D contributes, including "wireless services […] essential for citizens to function in the 21st Century" and "critical U.S. Government services and missions."[1] This Plan supports those goals.

This Plan does not direct actions or commit future resource investments by any branch of the federal government. Implementation of the recommendations in this Plan depends on decisions made in future federal budget processes.

Federal stakeholders of this Plan include the agency members of the Networking and Information Technology Research and Development (NITRD) Wireless Spectrum Research and Development Interagency Working Group (WSRD IWG). These are the agencies represented on the NITRD Subcommittee[2] that have investments related to wireless and spectrum research and development.

1.1 Scope

The following topics were selected for inclusion in this Plan:

- Key innovation areas – critical topics for spectrum research and development (R&D)
- Spectrum R&D accelerators – activities that enable faster spectrum R&D progress
- Organization of spectrum R&D – improvements to better structure spectrum R&D
- Glossary – terminology and definitions relevant for spectrum R&D

The following topics are important but are properly addressed elsewhere. They are mentioned at a high level where appropriate in this Plan:

- Standards
- Health effects of electromagnetic radiation
- Scientific integrity and public access
- Workforce development
- Citizen science activities

1.2 General Outcomes

In addition to the specific technical or other research outcomes of individual R&D activities, there are three general outcomes towards which all spectrum R&D activities should contribute.

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[1] The White House. 2023. *National Spectrum Strategy*. https://www.whitehouse.gov/wp-content/uploads/2023/11/National-Spectrum-Strategy.pdf.

[2] https://www.nitrd.gov/about/nitrd-contacts/representatives-and-alternates/

1.2.1 Deliver Broader Impacts for U.S. National Interests

Spectrum R&D should help the U.S. achieve the following:

- evolve the current spectrum management regime in ways that improve the benefits of the electromagnetic spectrum for all users;
- accelerate the pace of spectrum management evolution to facilitate innovation and economic growth;
- use data-driven decision making to improve outcomes;
- establish new models and systems for spectrum management that enhance U.S. economic growth and international standing;
- cooperate with international partners to leverage joint efforts for progress on challenges of mutual interest; and,
- utilize superior technical analysis and experimental data on proposed rules and techniques to support and influence decision-making in the International Telecommunications Union and other international bodies.

1.2.2 Foster a Field of Spectrum Science

Spectrum R&D should foster and sustain an interdisciplinary group of researchers in spectrum science who contribute in the following ways:

- perform research motivated by and related to current or future spectrum congestion and spectrum management challenges;
- draw on techniques from, and where appropriate to inspire basic research in, communications, sensing, networking, and other existing fields;
- go beyond technical focus to consider the direct and indirect impacts of interrelated technical, economic, social, health, environmental, and policy mechanisms and influences that affect spectrum evolution; and,
- contribute to the workforce development efforts needed for national leadership.

1.2.3 Support Spectrum Workforce Development

Spectrum R&D should foster development of the next generation of the spectrum workforce.

1.3 Revision Plan

This National Spectrum R&D Plan will be periodically revised in accordance with the following guidance.

The National Spectrum Strategy Implementation Plan of March 2024 states under Outcome 3.2(b), "The National Spectrum R&D Plan released under 3.2(a) will be revised. This effort will validate the process to refine and enhance the key innovation areas for spectrum R&D on an ongoing basis… Estimated Start: March 2025, Estimated Completion: 12 months."

The National Spectrum Strategy of November 2023 states, "This [National Spectrum R&D] Plan will consider recommendations developed through the collaborative framework outlined in Pillar Two. Specifically, stakeholders working through the framework will provide recommendations for conducting spectrum research that minimizes unnecessary duplication and helps to ensure all essential spectrum research areas are sufficiently explored.”

Spotlight 1.1: Guidance for the National Spectrum R&D Plan

The 2023 National Spectrum Strategy provides the following guidance for the Nation Spectrum R&D Plan.

Pillar Three | Unprecedented Spectrum Innovation, Access, and Management through Technology Development

> “Embracing and promoting innovative technologies that can expand the overall capacity or usability of spectrum is vital to our Nation. To accelerate innovation and improve our Nation’s understanding of electromagnetic phenomena, it is imperative for the spectrum research community to enhance the coordination of U.S. research and development endeavors and address areas where innovation is critical, including improving spectrum coexistence. As part of a whole-of-Nation endeavor, the U.S. will set measurable goals for advancing the state of technology for spectrum access, with an emphasis on dynamic forms of sharing [...]. The United States consistently has been a leader in scientific breakthroughs, including in spectrum-based technologies. By pursuing the below objectives, our Nation will uphold and extend its longstanding leadership in this dynamic sector.”

Strategic Objective 3.2 | Commit to improving collective understanding of the electromagnetic spectrum through coordinated, focused, and sophisticated research and development (R&D).

> “As a Nation, we must deepen our collective understanding of the electromagnetic (EM) spectrum—including radio frequency spectrum and beyond—if we are to meet the demands of our spectrum-dependent world. The U.S. Government will encourage and promote research and development that optimizes spectrum utilization, drives technological advancements, bolsters national security, informs effective policies, and advances scientific discovery. Real-world testing of dynamic sharing principles and the evolving technologies supporting them will provide a baseline for wider deployment and a way forward to develop shared spectrum methods, standards, technologies, and trust mechanisms in order to make dynamic sharing of spectrum scalable.
>
> The U.S. Government, through the White House Office of Science and Technology Policy and in coordination with the [f]ederal agencies, will develop a National Spectrum Research and Development Plan. This Plan will identify key innovation areas for spectrum research and development and will include a process to refine and enhance these areas on an ongoing basis.
>
> This Plan will consider recommendations developed through the collaborative framework outlined in Pillar Two. Specifically, stakeholders working through the framework will provide recommendations for conducting spectrum research that minimizes unnecessary duplication and helps to ensure all essential spectrum research areas are sufficiently explored. Increasing coordinated investment in research and development among government, academia, civil society, and the private sector will result in measurable advancements in state-of-the-art spectrum science and engineering. These efforts will further development of new methods for improving spectrum efficiency, advancing dynamic and secure spectrum access regimes, expanding use of cognitive radios using AI/ML [Artificial Intelligence/Machine Learning]-based techniques, and in other research areas.”

Part 2: Key Innovation Areas

This part of the Plan identifies high-value innovation areas for spectrum R&D. The areas are organized into the following categories:

- Spectrum Capabilities — Research to increase the performance and resilience of spectrum-dependent systems when operating in congested and shared spectrum environments
- Spectrum Science — Research to enhance the utilization and benefits of the radio spectrum for all users
- Integrative Innovation — Research that integrates innovations from multiple spectrum capabilities and spectrum science areas to address key end-to-end coexistence challenges
- Economics, Institutions, and Regulations — Research on economic, institutional, and regulatory issues associated with deploying, using, and managing spectrum innovations
- Systems and Solutions — Research toward systems and solutions that, if adopted and deployed widely, promise significant benefits for spectrum challenges

Two types of R&D are considered in this Plan:

- Use-Inspired Research — Work inspired by current or likely operational spectrum use cases, often linked to specific frequency bands, normally placing high importance on cost-effectiveness, and potentially coupled to specific application needs or constraints[3]
- Fundamental Research — Work that explores the frontier of possibility in spectrum science and engineering, sometimes resulting in unexpected payoffs that can occur decades later, and is normally driven by speculative ideas or the curiosity of researchers[4]

Use-inspired and fundamental research are both relevant in most of the key innovation areas. Other topics relevant for investigation in most of the key innovation areas include impacts of the new approaches on social priorities such as citizen privacy and protections, public awareness and acceptance, and digital equity for marginalized communities.

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[3] This description is an explication, appropriate for this context, of the general term *use-inspired basic research*, defined as "scientific investigation whose rationale, conceptualization, and research directions are driven by the potential use to which the knowledge will be put" in Stokes, Donald E. (1997) *Pasteur's Quadrant, Basic Science and Technological Innovation,* Brookings Institution Press.

[4] This description is an explication, appropriate for this context, of the general term *fundamental research*, defined as "work undertaken primarily for the advancement of scientific knowledge, without a specific practical application in view" (ibid).

2.1 Top Priorities

The full list of key innovation areas was informed by interagency consultation and public input submitted in response to a Request for Information (RFI). Each innovation area is described in more detail in the listed section numbers. The unordered priorities below represent a subset of the full list and are a consolidation of priorities recommended by federal agencies.

Key innovation areas for use-inspired research:

- Interference and Noise Resilience (2.3.3)
- Interference Impact Prediction (2.4.3)
- Sharing with Critical Systems (2.5.6)
- Regulatory Options (2.6.5)
- Advanced Spectrum Management Processes (2.7.4)

Key innovation areas for fundamental research:

- Agile Front Ends and Antennas (2.3.1)
- Spectrum Utilization Optimization (2.3.5)
- Undesired Signal Prediction (2.4.2)
- Spectrum Sharing Control (2.4.7)
- Cost of Interference (2.6.2)

The Spectrum Sharing Control innovation area includes research contributing to key integrative innovation challenges, e.g., sharing with passive systems and sharing with high power systems, that are described in Section 2.5.

2.2 Dynamic Spectrum Sharing (DSS)

There are many definitions of Dynamic Spectrum Sharing (DSS). In this National Spectrum R&D Plan, the term "dynamic spectrum sharing" means adaptive coexistence using techniques that enable multiple electromagnetic spectrum users to operate on the same frequencies in the same geographic area without causing harmful interference to other users (in cases where such users have an expectation of protection from harmful interference) by using capabilities that can adjust and optimize electromagnetic spectrum usage in real time or near-real time, consistent with defined regulations and policies for a particular spectrum band.

The 2023 National Spectrum Strategy identified DSS as a critical way to meet the growing demand for spectrum access. DSS is a broad approach. Most of the listed innovation areas contribute to advancing DSS. Because of the importance given to DSS in the National Spectrum Strategy, the relationship of each innovation area to DSS is explained in the detailed descriptions. R&D in many of the innovation areas contributes to other desirable outcomes in addition to DSS.

2.3 Spectrum Capabilities

This category of spectrum R&D investigates ways to increase the performance and resilience of spectrum-dependent systems when operating in congested and shared spectrum environments.

Use-inspired research on spectrum capabilities focuses on technical approaches to increase performance and resilience within current domestic and international rules and regulations.

Fundamental research on spectrum capabilities is not constrained by current domestic and international rules and regulations.

2.3.1 Agile Front Ends and Antennas

Priority key innovation area for fundamental research

Enable transmitters and receivers to operate across a wider range of frequencies and to change the operating frequency or band more quickly, with minimal impact to size, weight, power consumption, cost, or frequency selectivity.

This innovation area includes:

- tunable filters, power amplifiers, and array antennas;
- capabilities to transmit or receive multiple simultaneous signals at different frequencies; and,
- quantum apertures. [5]

Relationship to DSS: Agile front ends and antennas enable systems to exploit whatever frequencies become available via dynamic sharing mechanisms, then to rapidly re-tune to different frequencies when conditions change. Increased agility enhances system performance and resilience in spectrum sharing situations where spectrum access changes rapidly or unpredictably; and enables increased spectrum access for all users through permitting faster adjustments by spectrum sharing control systems.

2.3.2 Flexible Waveform Capabilities

Enable adaptation of transmitted or received signals across a wider range at each level of device size, power consumption, or cost.

This innovation area includes:

- hardware components for digital and analog computation, analog-to-digital and digital-to-analog conversion, and increased front-end dynamic range;
- software methods to synthesize new waveforms dynamically or at design time; and,
- control methods to select optimal waveforms for current conditions, rules, and regulations.

Relationship to DSS: Flexible waveform capabilities enable systems to adapt waveforms for increased performance and reduced interference as co-channel and adjacent-channel systems come and go in a dynamic shared environment.

[5] The general description of each innovation area, R&D accelerator, and organizational improvement is followed by examples introduced with the verb "includes." In all cases, this is to be interpreted as "includes but is not limited to."

2.3.3 Interference and Noise Resilience

Priority key innovation area for use-inspired research

Enable reception of desired signals despite higher levels of interference and noise at the output of the receive antenna than can be currently tolerated.

This innovation area includes physical layer approaches:

- new components, hardware designs, and signal processing techniques for receivers;
- cooperative methods where a receiver leverages data from or about interfering transmitters; and,
- variants of these solutions appropriate for upgrading existing systems.

This innovation area also includes higher layer approaches. For communications systems, higher layer approaches include interference-aware medium access control, routing, and transport algorithms. For sensor systems, higher layer approaches include interference flagging, cognitive radar, and other methods to protect data collection.

Cases of interest include interference from a small number of high-power devices and aggregate interference from a massive number of transmitters.

Relationship to DSS: Improved interference and noise resilience creates additional spectrum sharing opportunities and increases degrees of freedom available to spectrum sharing control systems.

2.3.4 Reliable Service from Variable Spectrum

Enable stable and effective system operation when available spectrum resources or characteristics change in real time, potentially due to spectrum sharing or dynamic optimization.

This innovation area includes:

- techniques for systems that operate in variable spectrum; and,
- techniques for hybrid systems that use a combination of static and dynamic spectrum access.

Relationship to DSS: Improving the quality of service that can be delivered using variable spectrum resources increases the types of systems and applications that can leverage spectrum opportunities provided by DSS, and thus increases demand and benefits for DSS.

2.3.5 Spectrum Utilization Optimization

Priority key innovation area for fundamental research

Enable systems to meet public mission or private industry business requirements with less impact on other spectrum users, through transmitter and system designs that cause less interference and receiver and system designs that experience less interference.

For transmitters, this innovation area includes methods to:

- focus transmissions into smaller slices of space, time, or frequency;
- create and control deep frequency nulls inside or adjacent to the operating bandwidth;
- reduce out-of-channel, out-of-band, and harmonic emissions; and,
- spread transmissions to reduce power density of emitted signals.

For receivers, this innovation area includes methods to:

- improve selectivity in space, time, or frequency;
- create and control deep frequency nulls inside or adjacent to the operating bandwidth;
- enable self-interference cancellation for full duplex operation, i.e., simultaneous transmit and receive on the same frequency;
- to receive widely spread transmissions; and,
- to reduce intermodulation effects.

For systems, this innovation area includes methods to:

- increase the information rate of wireless communications systems and the discrimination capability of sensor systems within fixed available bandwidth;
- increase spatial reuse of spectrum;
- leverage multiple antennas on a single transmitter/receiver and across systems (e.g., Multi-Input Multi-Output (MIMO) and distributed cooperative antennas); and,
- improve coverage using reconfigurable intelligent surfaces.

For applications, this innovation area includes ways to accomplish mission goals while using low-impact transmitter, receiver, and system designs.

Relationship to DSS: Spectrum utilization optimization creates additional spectrum sharing opportunities and reduces constraints placed on spectrum sharing control systems.

2.3.6 Millimeter Wave and Above

Enable effective usage of novel spectrum including millimeter wave, sub-terahertz, terahertz, and optical frequencies, at size, power, and cost levels acceptable for important applications.

This innovation area includes hardware components and new device, signal, and higher-layer designs appropriate for the propagation and environmental effects of these novel spectrum bands.

Relationship to DSS: The unique propagation and antenna physics at millimeter wave and above creates new options for dynamic uses and applications requiring different DSS solutions in these bands.

2.4 Spectrum Science

Innovations in the following areas improve the utilization and benefits of the radio spectrum for all users.

This category of spectrum R&D investigates methods and techniques that improve spectrum management and control systems, the design of spectrum sharing solutions and regulations, and future certification and assurance processes. Like "computer science," the term spectrum science describes a discipline that spans a wide range from natural science to creative engineering. Spectrum science includes the science of spectrum modeling, monitoring, and analysis; the engineering of systems for automatic management, control, and protection of spectrum; and verification, security, and privacy solutions for spectrum systems and information. Many spectrum science innovations are also useful for individual spectrum users that seek to observe, predict, or control interactions with other systems.

2.4.1 Propagation Prediction

Estimate signal levels across space given transmission from a specified location (see Spotlight 2.1).

This innovation area includes:

- developing new path loss and clutter modeling methods, such as use of big-data Geographic Information Systems (GIS), foliage maps, high-resolution topography, and building data;
- development of models for specific bands and environments; and,
- real-world measurement campaigns to generate the data for both endeavors.

Relationship to DSS: Improved propagation prediction reduces uncertainty, which allows the sharing control mechanism to leverage spectrum more efficiently while adequately protecting existing users.

2.4.2 Undesired Signal Prediction

Priority key innovation area for fundamental research

Estimate undesired signal levels at spatial locations and times, including aggregate interference (see Spotlight 2.1).

This innovation area combines propagation prediction with models of emitter systems, including their distribution and mobility, emissions based on traffic and load, and spectrum capabilities including frequency agility, waveform flexibility, and spectrum utilization optimization.

Relationship to DSS: Improved undesired signal prediction enables the technical regulations and control system for a shared band to offer more spectrum access opportunities, because the extra separation between systems required to tolerate unknown signal level variations can be reduced.

2.4.3 Interference Impact Prediction

Priority key innovation area for use-inspired research

Estimate interference impact on victim systems at the technical level (see Spotlight 2.1).

This innovation area combines prediction of undesired signals with models of receiver systems, including their distribution and mobility, traffic and load, interference resilience capabilities, and system-specific technical metrics for service quality degradation. This innovation area also includes models of how emitter and receiver systems adapt their operations in response to each other's emissions and actions.

Ultimately, spectrum management decisions must consider interference impact at the level of harm to the user's mission or harm to societal goals, not just at the technical level. Translating technical impact into those broader impacts is the subject of an innovation area described later (Cost of Interference, Section 2.6.2).

Relationship to DSS: Improved interference impact prediction creates more spectrum access opportunities, because higher power undesired signals can be dynamically allowed at places and times where they do not excessively impact the real-world operations of the victim system.

Spotlight 2.1: Predictive Modeling in Spectrum Science

Predictive modeling plays a crucial role in the design and development of spectrum dependent systems and control methods, encompassing various functions such as propagation, interference, parameter, and traffic estimation. Traditionally, classical modeling techniques have relied on analyzing large datasets and employing mathematical methods and statistics to understand and represent the relationships within the data. This approach typically involves using equation-based models to describe the phenomena being studied.

In recent times, computational methods, particularly those involving machine learning, have provided alternative paths to enhance predictive modeling. Machine learning techniques can process vast amounts of data to predict future outcomes without necessarily relying on predefined models. This capability allows for more flexible and dynamic prediction approaches.

These prediction techniques can be extended to provide risk-based assessments, in which probability density functions are carried through the analysis in order to provide grounded estimates of the risk of undesirable outcomes. Risk-based assessments have become a high priority as congestion drives closer packing of spectrum users.

Classical mathematical models and modern machine learning techniques can be deployed in settings ranging from off-line statistical predictions to online near-real-time assessments. Online assessments can rely on data collected in advance or can leverage feedback from measurements and telemetry. Online operation and use of feedback to enhance accuracy become more important as the use of dynamic spectrum sharing increases.

Regardless of the prediction method used—whether classical mathematical models or modern machine learning techniques, whether simple statistics or risk-based modeling, whether offline statistical predictions or online assessment leveraging real-time feedback—validation remains a critical step. Validation is essential to ensure the accuracy and reliability of predictions and is generally performed using mathematical theory and/or ground truth measurements. This process ensures that the models or techniques used provide dependable and accurate predictions.

Research on the various prediction methods and validation approaches is important in each of the predictive modeling areas listed under Spectrum Science.

2.4.4 Spectrum Monitoring at Scale

Enable over-the-air collection and access to collected information by public and private stakeholders regarding federal and non-federal spectrum usage, to the extent feasible and allowable by statutory limitations. The data may serve various objectives including research, real-time operations, interference detection, and regulatory decisions.

This innovation area includes:

- spectrum monitoring systems and data storage systems;
- low-level analysis of monitoring data including detection and classification of signals;
- telemetry methods and processing;
- fusion of monitoring and telemetry data;
- hardware and systems enabling high-quality sensors, low-cost sensors, and cost-effective network combinations of the two;
- secure protocols for spectrum data exchange; and,
- distributed sensing algorithms.

The phrase “at scale” has two meanings, both of which are important areas for innovation: (1) cost-effective coverage of large areas, wide frequency ranges, and/or long durations; and (2) cost-effective measurement of fine details, e.g., effective spectrum monitoring when usage varies rapidly in space and time or when multiple users are tightly interleaved.

Relationship to DSS: Increasing the scale and affordability of spectrum monitoring increases the amount and quality of the underlying data used for all activities listed in the next sections, and thus enhances the benefits achieved in all those areas.

Spotlight 2.2: Artificial Intelligence and Machine Learning (AI/ML) in Spectrum R&D

AI/ML capabilities are a tool applicable to many of the key innovation areas listed in this National Spectrum R&D Plan. Some potential AI/ML applications include:

Agile front ends and antennas	Accelerate exploration of innovative hardware designs
Receiver interference rejection	Integrate diverse sensed and received data streams, control sophisticated rejection strategies
Millimeter wave and above	Integrate diverse situational awareness data, use it to overcome propagation challenges
Flexible waveform capabilities	Control waveform adaptation, synthesize new waveforms
Reliable service from variable spectrum	Predict imminent changes in spectrum availability
Propagation modeling	Incorporate new information sources such as big-data GIS, foliage maps, high-resolution topography, and building data
Spectrum situational awareness at scale	Interpretation and interpolation of available data streams, control available resources for maximum situation awareness payoff
Spectrum data analysis	Analyze spectrum data in real time to drive automated decisions for efficient spectrum usage
Safe sharing of sensitive information	Generate synthetic data that preserves critical information while obscuring sensitive information
Spectrum sharing control	Detect and respond to failures and attacks
Fast interference management	Detect interference, analyze source, plan response

2.4.5 Spectrum Data Analysis

Interpret spectrum monitoring data to provide comprehensive spectrum situational awareness.

This innovation area includes:

- spatial science and interpolation techniques to maximize situation awareness quality for a given investment in sensors, data collection, computation, and storage;
- cost-effective fusion of monitoring data with regulatory and other databases;
- tracking, characterization, and identification of transmitting systems;
- anomaly detection;
- threat identification and assessment;

- design and usage of edge computing platforms for distributed analysis computations;
- standards and protocols for exchange of analytic products; and,
- use and support of Artificial Intelligence and Machine Learning (AI/ML) in all these areas.

Relationship to DSS: Improved spectrum data analysis enhances the speed, affordability, and quality of spectrum situational awareness used for all the activities listed in the next sections, and thus enhances the benefits achieved in all those areas.

2.4.6 Spectrum Digital Twin

Create digital twins for observables of interest in specific spectrum situations.

A digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin.[6]

This innovation area focuses on simulations that give accurate predictions, normally achieved by incorporating all significant entities and interactions from the real-world situation. This requires collecting or tracking significant information about the situation of interest. An accurate digital twin enables a quantum leap in control and predictability of the real-world spectrum system compared to what is possible using the partial models that have historically been available.

Spectrum digital twins depend on advanced predictive models informed by affordable at-scale spectrum monitoring and data analysis. Spectrum digital twins must account for all propagation modes, even those that occur only rarely. Building accurate digital twins thus requires propagation data collected over longer time durations and from more locations than is currently available in most datasets.

Relationship to DSS: Cloud-enabled fully-software spectrum digital twins enable rapid and scalable iterative improvement of spectrum sharing regulations and spectrum sharing control systems, by facilitating experimentation that is faster and more affordable than over-the-air prototyping. Hardware-based spectrum digital twins enhance the ability of spectrum sharing control systems to accurately predict outcomes of control decisions in real time, enabling management systems to provide more spectrum access opportunities while reducing interference risk.

2.4.7 Spectrum Sharing Control

Priority key innovation area for fundamental research

Manage or advise independent spectrum-dependent systems, with appropriate consent from relevant stakeholders, so they can effectively operate in the same frequency band and geographical area.

The term spectrum sharing control is used rather than dynamic spectrum management system because future spectrum sharing control systems and methods may be centralized, decentralized, or hybrid; and may implement cooperative or non-cooperative spectrum sharing approaches. Current spectrum

[6] National Academies of Sciences, Engineering, and Medicine. 2024. *Foundational Research Gaps and Future Directions for Digital Twins*. The National Academies Press. https://nap.nationalacademies.org/catalog/26894/foundational-research-gaps-and-future-directions-for-digital-twins

sharing control systems focus almost entirely on ex ante interference prevention. Future spectrum sharing control systems may include ex post interference detection and response, where acceptable, to increase spectrum access.

This innovation area uses results from other spectrum science innovation areas (including propagation, undesired signal, and interference impact prediction; spectrum monitoring and data analysis; spectrum digital twins; fast interference management; and security and privacy solutions) to create spectrum sharing control systems and methods that:

- maximize spectrum access while achieving required interference levels;
- improve predictability of spectrum access to enable use of dynamic shared spectrum by users with specific mission or business assurance needs;
- enhance cyber-physical resilience or "the capability of an integrated system to keep running—even if not at peak performance—should it lose specific functions [whether due to] component failures, human errors, natural disasters, or malicious attacks";[7]
- enhance the energy efficiency of the spectrum control system and the systems it controls
- improve outcomes when decisions are highly constrained through assessing risk associated with prospective decisions;
- maximize benefits of spectrum decisions for mission or business goals through linkage to mission or business management systems while maintaining privacy and security;
- increase effectiveness of operator oversight and control through improved user interface and machine interface design;
- achieve evolvability and flexibility through use of advanced representations for exchange and processing of spectrum control information, e.g. digital policy sets and spectrum consumption models;
- reduce decision latency, potentially to milliseconds, to enable utilization of shorter spectrum access opportunities and faster reaction to environmental changes; and,
- support short-duration spectrum sharing transactions, potentially sub-second, to reduce incumbent concerns about loss of optionality from long-duration transactions and thus facilitate adoption of spectrum sharing.

This innovation area also includes research on analysis and assessment of spectrum sharing control systems, including ways to predict or measure:

- the amount and distribution of spectrum access provided to specified systems in current conditions or in predicted future situations;
- how much autonomy can be safely delegated to the system;
- the harm caused by potential component or subsystem failures; and,
- the level of human involvement required to accomplish desired outcomes while complying with applicable rules and regulations.

Relationship to DSS: Spectrum sharing control is the core capability for dynamic spectrum sharing.

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[7] President's Council of Advisors on Science and Technology. 2024. *Strategy for Cyber-Physical Resilience: Fortifying Our Critical Infrastructure for a Digital World*. https://www.whitehouse.gov/wp-content/uploads/2024/02/PCAST_Cyber-Physical-Resilience-Report_Feb2024.pdf

2.4.8 Fast Interference Management

Detect, analyze, attribute, locate, and mitigate interference problems quickly enough to protect mission success or service quality of the interference victim.

Fast interference management solutions, which include spectrum situational awareness and mitigation methods, improve the ability of regulators, spectrum managers, and enforcement entities to protect the spectrum. They may also be used in future spectrum sharing automated control systems.

This innovation area includes mitigation of accidental, unintentional, incidental, and malicious interference. Mitigation methods include:

- emitter and victim automated adaptation;
- methods for victims to inform interferers and spectrum control systems about detected interference; and,
- may include regulatory requirements and enforcement on emitters and on spectrum sharing control mechanisms to enable fast interference mitigation.

Relationship to DSS: Automatic enforcement of spectrum sharing rules and agreements, and automatic detection and mitigation of erroneous or malicious spectrum use, increase trust by all stakeholders facilitating the adoption of more efficient spectrum sharing mechanisms. Automatic detection and mitigation of interference, before or soon enough after it exceeds tolerance thresholds to preserve service quality, increases spectrum access in dynamic shared bands by reducing required ex ante separation margins.

2.4.9 Spectrum System Assurance

Ensure that designs in the above areas meet requirements, and that deployed systems behave as designed.

This innovation area includes:

- modeling and simulation environments with both physical layer and higher layer interactions;
- cost-effective testing techniques that can overcome the high complexity of spectrum access subsystems and spectrum control mechanisms, both individual-system and distributed; and,
- techniques to provide high assurance that problematic systems are taken off the air quickly, especially for proliferated low-power devices.

Goals of work in this area include convergence on standard assurance tools and processes for use in future development and certification activities.

Relationship to DSS: Improved assurance capabilities increase incumbent trust that their spectrum access equities will be protected, and thus increase stakeholder willingness to agree to dynamic spectrum sharing arrangements. Improved assurance capabilities also enable safe deployment of more complex spectrum sharing control solutions; the increase in permissible complexity enables use of more sophisticated approaches that increase spectrum access in challenging shared bands.

2.4.10 Safe Sharing of Sensitive Information

Enable protection of individual privacy, mission agency operational security, and commercial user proprietary information while sharing spectrum with or coexisting closely with other systems.

New information protection challenges arise in many of the innovations that help overcome spectrum congestion. These challenges include the increased information exchange and observables associated with spectrum sharing, information collected by spectrum monitoring and fast interference management mechanisms, information shared through telemetry that informs interference modeling and mitigation, and dataset compilation and sharing for R&D.

This innovation area includes:

- obfuscation and obscuration techniques, specialized to each application or activity to preserve its end-to-end capability;
- study of the fundamental tradeoffs between necessary information leakage and spectrum sharing effectiveness, specialized to each application or activity;
- transparency mechanisms and auditing methods for data collection and analysis, so stakeholders can detect and enforce limits on misuse;
- data security methods that facilitate sharing and utilization of accurate data without sacrificing privacy (e.g., multiparty computation); and,
- solutions for general issues called out in the NIST data privacy framework that leverage special characteristics and respond to the special risks of spectrum data.

Relationship to DSS: Information sharing is a necessary component and unavoidable side effect of spectrum sharing. Concerns about sharing of sensitive information have been a major constraint on the progress of DSS, particularly from the perspective of federal agencies with sensitive missions. Research on safe sharing of sensitive information will help overcome these concerns, with the potential to further increase spectrum access by refining the coarse restrictions currently imposed to prevent information leakage. Research on safe sharing of sensitive information also helps prevent future citizen privacy impacts of DSS.

2.4.11 Spectrum System Security

Protect the systems and data that control and support spectrum access and management from malicious influence or disruption.

Spectrum is a key resource enabling critical command, control, and sensing functions. This makes spectrum systems and data attractive targets for malicious actors seeking to influence or disrupt other vital activities.

This innovation area has two primary aspects:

- protecting spectrum management and control systems and data as a networked information system (e.g., using zero-trust architectures) and
- protecting them as a cyber-physical system (e.g., using sensor voting protocols). A key challenge is developing protection techniques that offer adequate security while enabling lawful intercepts and other critical functions.

Relationship to DSS: Spectrum control systems for DSS offer high attack amplification: a small disruption to the spectrum control system for a shared band can deny or disrupt spectrum access for many spectrum users or systems over a wide geographic area. This makes spectrum control systems especially attractive targets for attackers and a key point of vulnerability for legitimate users. Security of spectrum control systems is therefore essential for safe adoption of dynamic spectrum sharing, for the willingness of new entrants with high-value applications to rely on dynamic shared spectrum, and for the willingness of incumbents with critical missions to agree to spectrum sharing arrangements.

2.5 Integrative Innovation

Work in the following areas integrates innovations from spectrum capabilities and spectrum science research to address key end-to-end coexistence challenges.

This category of spectrum R&D focuses on in-band and adjacent-band spectrum sharing solutions specialized for systems or applications that have unique characteristics. In some integrative innovation areas, the incumbent user type or mission shapes the unique spectrum sharing challenges. In other areas, characteristics of the new entrant systems or opportunistic receivers drive the requirements or opportunities. Innovations from multiple integrative innovation areas listed below can be combined where appropriate, e.g., introduction of low-power systems into a radar band.

Relationship to DSS: Solutions to integrative innovation challenges will enable introduction or expansion of dynamic spectrum sharing in many situations where it is infeasible or limited today.

2.5.1 Sharing with Radar

Improve coexistence of radar and other spectrum dependent systems. One challenge of high importance is coexistence of radar and communications below 10 GHz.

This innovation area includes:

- co-channel and adjacent-band coexistence issues;
- temporal sharing and interference resilience approaches; and,
- joint sensing and communications, particularly solutions that implement functions currently provided by high-power standalone radars.

2.5.2 Sharing with Low-Power Systems

Improve coexistence of proliferated low-power systems such as user-deployed Wi-Fi and the Internet of Things with other spectrum dependent systems. One challenge of high importance is coexistence of low-power systems with sensitive receivers such as GPS, satellite communications, or radar.

This innovation area includes methods to address the challenges that arise when one side of a spectrum sharing arrangement is a high number of low-cost devices without central control. These challenges include special regulatory, technical, and political issues that affect spectrum sharing control and interference management.

This innovation area also includes methods to safely leverage enhanced propagation loss conditions, e.g., the higher loss experienced when the low-power devices operate indoors.

2.5.3 Sharing with High-Power Systems

Enable introduction of high-power communications systems, for example, full-power International Mobile Telecommunications (IMT) Cellular, into reallocated or repurposed bands with incumbent users.

This innovation area includes:

- methods to leverage existing standardized capabilities in new coexistence and sharing scenarios, e.g. Physical Resource Block blanking, beam steering, and dynamic frequency control;
- methods to leverage emerging system design approaches such as the Open Radio Access Network (ORAN) to achieve better spectrum sharing;
- methods to preserve optimization of communications system functions when operating parameters are changed, potentially rapidly, to implement spectrum sharing;
- cost-effective improvements to the incumbent systems to increase spectrum access for the introduced systems; and,
- technical features such as audit trail mechanisms supporting predictable spectrum access and effective dispute resolution procedures for all parties.

2.5.4 Sharing with Non-Terrestrial Systems

Improve coexistence of terrestrial, airborne, and space-based spectrum dependent systems, including space-to-space, air-to-space, and space-to-ground sharing.

This innovation area includes:

- coexistence of communications, navigation, radar, and passive systems used for scientific research or environmental monitoring;
- communications sharing among independent operators including geostationary/non-geostationary sharing; and,
- integrated space-air-ground networks. It also includes new spectrum management techniques appropriate for millimeter wave and higher frequency bands.

2.5.5 Sharing with Passive Systems

Improve coexistence of services that actively transmit, particularly communications and radar, with receive-only passive systems that often have sensitive receivers, such as scientific instruments and weather satellites.

This innovation area includes:

- methods to limit emissions and assess and mitigate out-of-band emissions from adjacent-band systems, which are significant problems due to the sensitivity of passive systems and
- modeling of coexistence with receivers that measure channel characteristics using signals of opportunity (e.g., GNSS/GPS) and methods to mitigate interference challenges they experience.

2.5.6 Sharing with Critical Systems

Priority key innovation area for use-inspired research

Enable safe introduction of spectrum dependent systems that optimize criteria, such as cost or performance, into bands with critical infrastructure or systems that require high availability to support critical missions.

This innovation area includes:

- special validation and testing, security, and fast interference management approaches for the systems being introduced;
- appropriate spectrum sharing control and situational awareness mechanisms, including specialized information protection and cyber-physical security approaches; and,
- cost-effective enhancements to the critical systems to help overcome sharing challenges.

2.5.7 Critical System Spectrum Operations

Assure spectrum access and sensitive information protection in ways appropriate for systems that require high availability to support critical missions.

This innovation area includes:

- ways for the critical systems to achieve reliable service from variable spectrum;
- specialized variants of Spectrum Data Analysis and Spectrum Sharing Control solutions that focus on high availability in complex congested or contested environments;
- specialized variants of Safe Sharing of Sensitive Information and Spectrum System Security solutions appropriate for the high threats facing critical systems; and,
- resilient spectrum access in the presence of adversarial attempts to detect, disrupt, or intercept the critical system's transmissions.

2.6 Economics, Institutions, and Regulations

Research in the following areas investigates economic, institutional, and regulatory issues associated with deploying, using, and managing spectrum innovations.

This category of spectrum R&D provides understanding, analytic methods, and creative approaches that help planners and policy makers overcome the non-technical barriers that slow or prevent adoption of spectrum innovations, and that help various spectrum stakeholders effectively protect their equities in an environment of competing spectrum users with divergent interests.

2.6.1 Value of Spectrum

Estimate the overall benefits of spectrum allocation and usage decisions relative to national priorities, enabling comparison across services and social sectors.

This innovation area includes:

- development of metrics for spectrum efficiency and spectrum utilization;
- methods to estimate those metrics, as well as to quantify the benefits and costs of spectrum allocation decisions for balancing national priorities; and,

- models and econometric analyses of the value of licensed spectrum, shared spectrum, unlicensed spectrum, and usage by entities serving public interests such as national defense, environmental monitoring, and scientific research.

Research in this area provides fundamental understanding that supports progress toward Outcome 2.2(a) of the National Spectrum Strategy Implementation Plan, "A value-based model to inform spectrum policy decisions."

2.6.2 Cost of Interference

Priority key innovation area for fundamental research

Estimate impacts of interference relative to national priorities, enabling comparison across services and social sectors.

This innovation area includes:

- development of metrics to measure the impact of interference on spectrum user missions or user interests;
- methods to estimate those metrics based on predicted technical interference impact or interference risk assessment; and,
- ways to compare the relative cost to national priorities of impacts to different users or missions.

Research in this area provides fundamental understanding that supports progress toward Outcome 2.2(a) of the National Spectrum Strategy Implementation Plan, "A value-based model to inform spectrum policy decisions."

2.6.3 Mechanism and Market Design

Identify, consider, and evaluate effectiveness of incentives and interactions of actors associated with innovations in spectrum technology and policy.

This innovation area includes:

- economic and behavioral research on incentive-compatibility, strategy-proofness, and mechanism feasibility based on technological constraints;
- market designs including multi-unit auctions, bilateral auctions, and other ways to enhance economic efficiency;
- incentives for sharing by private and public entities and for public entities to update legacy systems toward better spectrum sharing support;
- incentives for data collection and sharing;
- new technologies for institutional interaction including microtransactions, distributed ledgers, automated service-level agreements, and smart contracts; and,
- competition preservation mechanisms to prevent collusion among users and to ensure impartiality of spectrum control system operators.

Relationship to DSS: Successful dynamic spectrum sharing requires aligning the incentives of actors and interaction mechanisms that generate the desired emergent behaviors and market dynamics, in addition to effective technical approaches. Research in this area helps identify opportunities and will contribute to the co-design of technical, economic, and regulatory solutions that is essential for long-term success of DSS.

2.6.4 Spectrum Sharing Risk and Adoption

Design and analyze spectrum sharing arrangements that stakeholders are willing to adopt with a focus on economic, institutional, and regulatory risk management.

This innovation area includes:

- risk analysis and methods to reduce risk to an acceptable level analyzed from the perspective of each of the participants in a sharing arrangement e.g., incumbents and new entrants;
- efficient ex ante and ex post approaches for enforcing agreements at the technical and institutional levels, e.g., new automatic adjudication methods; and,
- agent-based modeling and other empirical research methods to evaluate risk thresholds and adoptability of new sharing solutions.

Research in this area provides fundamental understanding that supports progress toward the incentive issues addressed in the National Spectrum Strategy: "updating the incentives of all spectrum users is a critical component for U.S. economic growth and technological competitiveness. NTIA, in collaboration with the FCC [Federal Communications Commission] and industry, will study the commercial incentives associated with different approaches to spectrum sharing to ensure that approaches to dynamic spectrum sharing incorporate economic considerations."

Relationship to DSS: This research area helps policymakers identify DSS options that reduce resistance from stakeholders, and thus accelerates adoption of DSS.

2.6.5 Regulatory Options

Priority key innovation area for use-inspired research

Create and analyze innovative spectrum regulatory approaches.

This innovation area includes:

- exploration of new property, access, and sharing rights;
- new rules and rule systems; economic and incentive analysis of regulatory approaches;
- applicability of regulatory approaches to different bands and propagation regimes; and,
- methods to assess impacts of regulatory approaches and spectrum access regimes on service utility and desirability.

Research in this area provides fundamental understanding that supports progress toward Outcome 3.3(a) of the National Spectrum Strategy Implementation Plan, "Policy initiatives to maximize regulatory flexibility to promote U.S. technological innovation and opportunistic sharing."

Relationship to DSS: This research area enables regulators to better manage and promote spectrum innovations, including DSS.

2.7 Systems and Solutions

This category of spectrum R&D includes research toward future systems and solutions that, if adopted and deployed widely, promise to help resolve spectrum challenges among their other benefits for their users and society. Adoption and deployment of the systems and solutions is outside the scope of spectrum researchers and research sponsors. However, the research community can significantly contribute toward these desirable outcomes through investigating the research topics listed in this section that inform the design and use of the future standards, solutions, and systems.

2.7.1 Sharing-Capable 6G

Research toward 6G standards that enhance operation in dynamic spectrum, to maximize efficiency in different spectrum sharing arrangements while delivering high service quality to a diverse set of users.

This goal refers to enhancing sharing between 6G and non-3rd Generation Partnership Project (3GPP)[8] systems. Sharing among 6G and other 3GPP technologies and networks is a high priority for operators and will be achieved without national R&D coordination.

R&D toward this goal includes efforts at the physical and resource management layers and in the network core; metrics for proposed 6G standards elements and candidate implementations, such as the ratio of exclusive to dynamic spectrum required to deliver high user service quality; and methods to leverage emerging standardized capabilities for new coexistence and sharing purposes, e.g., Artificial Intelligence (AI)-Native Air Interface and Integrated Sensing and Communications.

Relationship to DSS: Commercial telecommunications providers are significant users of spectrum. Enhancing spectrum sharing capabilities in next generation mobile systems will create new opportunities for dynamic spectrum sharing in heavily congested portions of the spectrum.

2.7.2 National Spectrum Data Ecosystem

Research toward linking systems that generate, process, and consume spectrum data into a federated national architecture supporting R&D, spectrum management, and operations.

Diverse federal and non-federal entities collect, share, store, and process spectrum data with different access controls and with different payment mechanisms for that data. A national-scale federated data processing system will enable evolvable online and offline processing, sharing of spectrum data and derived products, and easier discovery and reuse of available resources.

The national ecosystem may eventually include, among other data, monitoring data, telemetry, predictive models, models of spectrum dependent systems, and real-time propagation measurements.

Development of the architecture includes standardization of data representations, protocols, access methods, identification and authorization methods, audit trail mechanisms, and cloud- and edge-computing platforms that support moving computation to the data when needed. This work draws on the common representations and protocols from the R&D community (see Part 3: Spectrum R&D Accelerators) but goes further since the selected standards must be adopted by non-R&D communities including spectrum policy, regulatory, management, and operations.

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[8] https://www.3gpp.org/about-us

Relationship to DSS: Broader availability and sharing of spectrum data is valuable to inform dynamic spectrum sharing R&D, planning, and spectrum sharing control. A national spectrum data ecosystem will reduce the cost for each user or application to access the data it needs, and thus will facilitate broader adoption of DSS.

2.7.3 Evolvable Spectrum Control System

Research toward a modular open platform for spectrum sharing control that can be easily evolved or extended to rapidly add support for new bands.

R&D is needed toward a system that:

- has open interfaces and uses open standards including mechanisms for preemption and prioritization;
- supports federal-to-federal sharing in addition to federal-to-non-federal sharing;
- safely exports data for R&D;
- allows experimentation with new components or approaches embedded in the larger operational system; and,
- facilitates information sharing, for example between FCC and NTIA systems, including automated information sharing using Application Programming Interfaces (APIs) and structured datasets.

Relationship to DSS: Adoption of an evolvable spectrum control system by regulators would significantly accelerate deployment of DSS in new bands. Otherwise, the spectrum control system must be built from scratch for each band, which is an expensive and slow process. Use of an evolvable system would also enhance trust in proposed DSS arrangements and thus facilitate their adoption. Stakeholders would have prior experience with the sharing control system, enabling them to predict its behavior and the costs of building support for it into other systems. Use of an evolvable system with open interfaces and standards also enables growth of a larger ecosystem of DSS tools and systems that interact with the spectrum control system, apply across bands, and gain economies of scale.

2.7.4 Advanced Spectrum Management Processes

Priority key innovation area for use-inspired research

Research toward automated processes that enhance support for automatic spectrum management and spectrum sharing systems, and that enable new spectrum management approaches for non-terrestrial sharing, novel spectrum bands, and similar innovations.

This solution area includes:

- evolution of spectrum management practice toward machine-readable band rules;
- establishing quantitative thresholds that distinguish acceptable vs. unacceptable unwanted signals; and,
- standardization of APIs enabling machine-to-machine interfaces between external stakeholders and regulatory systems.

Relationship to DSS: Evolving spectrum management practice will enable more effective DSS solutions.

2.7.5 Regulatory and Technical Specialization for Verticals

Research toward synergistic regulations, spectrum sharing solutions, and spectrum monitoring and control systems for operating environments that have unique characteristics.

This solution area includes specialization of regulations and technical solutions for rural and tribal areas, including:

- remote education and health care delivery applications and
- for verticals including agriculture, educational facilities, hospitals, manufacturing facilities, chemical and resource plants, and mining and underground operations.

Relationship to DSS: Specialization for the needs of verticals will foster adoption of DSS in environments that are difficult to support today.

Part 3: Spectrum R&D Accelerators

Effective spectrum research and development depends in part on the availability of appropriate research infrastructure and enablers. Investment in these research accelerators can have high payoff in innovation speed and quality if appropriate structures and incentives are established for support and use of common solutions.

3.1 Top Priorities

The full list of spectrum R&D accelerators was informed by interagency consultation and public input submitted in response to an RFI. Each accelerator is described in more detail in the listed section number. The unordered priorities below represent a subset of the full list and are a consolidation of priorities recommended by federal agencies.

- Public Datasets (3.2.1)
- Testbeds and Testing Frameworks (3.3.4)
- Spectrum TRL Pipeline Review (3.4.1)

3.2 Data

The following data accelerators support alignment of R&D with real-world problems and enable new approaches such as AI/ML based solutions. A key issue to be addressed in all data accelerator activities is citizen privacy and protection.

3.2.1 Public Datasets

Priority accelerator

Valuable datasets include:

- measurements (particularly those labeled with ground truth) of spectrum environments, spectrum dependent systems, spectrum sharing situations, anomalies, failures and attacks;
- information about and from currently operating equipment and distributed systems; and,
- examples of deployments, missions, and traffic or operating loads.

This accelerator includes:

- collection, labeling, and curation of data sets;
- application of results from the sensitive information protection key innovation area; and,
- development of open-source spectrum data sharing APIs to harmonize the way data is shared and retrieved.

Selection of data sets to gather and publish is tightly coupled to the prioritization of R&D in the various key innovation areas, particularly for any priority areas where AI/ML is to be used (see Spotlight 2.2).

Data sets already held by regulators, such as on spectrum usage, have potentially high value for R&D. Regulatory agencies should pursue focused initiatives to curate and release regulatory data where permitted.

3.2.2 Public Data Repositories

Public data sets are most valuable if they are easily discoverable and retrievable.

This accelerator includes:

- design of repositories and indexing mechanisms;
- support for the storage and bandwidth needs of operating repositories; and,
- further application of results from the sensitive information protection key innovation area.

3.2.3 Common Representations and Protocols

Public data sets and repositories are most valuable if they use widely shared data representations, meta-data standards, and access protocols. Use of a common data model shared between laboratory, virtual experiments, and field testbeds accelerates R&D by facilitating smooth transition of projects through these stages. Widespread use of common representations and protocols by the R&D community also helps mature them towards future use in a national spectrum data ecosystem.

This accelerator includes:

- development of generalized, expressive, and effective ways to represent the public datasets described in Section 3.2.1; and,
- protection of data at rest and in motion to make it harder for adversaries to corrupt it.

The accelerator draws on research from the spectrum situational awareness at scale innovation area and multiple other areas. It goes beyond the R&D innovation areas in its goal to select common representations and protocols for use in public datasets and repositories.

3.3 Tools and Facilities

The following R&D accelerators are critical tools and facilities needed by spectrum researchers and developers.

3.3.1 Spectrum Sharing Simulator

Open, modular, extensible, shared simulation environments have demonstrated unparalleled value for accelerating R&D in other fields such as networking. They are essential for frictionless reproducibility of published results, which further accelerate progress. Similar benefits are anticipated for spectrum sharing control and other advanced spectrum R&D topics if a computationally feasible spectrum sharing simulation environment is made available.

A key attribute is that the simulation should be fully implemented in software without dependence on non-scalable physical hardware such as a channel emulator, so researchers can use the public cloud to scale up to large simulations or to achieve the high level of parallelism required for AI/ML training.

This accelerator includes a focus on developing a library of shared models of different systems and operating environments at different levels of fidelity and across a wide range of probabilities, enabling rapid investigation of various scientific questions and frictionless reproducibility of results.

3.3.2 Flexible Radios for R&D

Academic laboratories and small businesses can only participate in experimental R&D on a band if they have access to cost-effective, flexible radio platforms capable of transmission and reception in the band.

This accelerator includes establishing a process for federal and non-federal stakeholders to identify upcoming bands of interest for which there are gaps and to convene the research community to develop realistic requirements for the necessary radio platforms.

3.3.3 High-Performance Open Platforms

Academic laboratories and small businesses can only impact leading-edge commercial and government needs if they have access to open stacks and interfaces capable of implementing high-performance, commercial- or government-equivalent system capabilities.

This accelerator includes processes and efforts to add necessary R&D support capabilities to commercial and government platforms and to add high-performance capabilities to existing open R&D platforms.

3.3.4 Testbeds and Testing Frameworks

Priority accelerator

Advancing a technology or solution to higher technology readiness levels or gathering experimental data to discover new approaches often requires at-scale over-the-air testing beyond the in-house capability of most R&D laboratories. Publicly-available testbeds and testing frameworks are an essential resource.

This accelerator includes:

- creation, sustainment, enhancement, and coordination of testbeds;
- creation of common execution environments and data models enabling smooth transition of experimentation between simulation and test or across testbeds;
- linkage of separate testbeds supporting simultaneous live, virtual, constructive testing, and training;
- documentation and other investments that enhance discovery of and access to testbed capabilities;
- remote access test capabilities; and,
- work on common tools that can be shared across testbeds.

Note that data exchange requirements (e.g., amount, resolution, latency) differ between testing and training communities.

Testbed investments should be focused on developing or enhancing specific capabilities that advance spectrum research toward identified research questions or data to be gathered, for example, real-world testing of dynamic spectrum access and management systems.

Testbeds and testing frameworks should consider the integration with spectrum digital twins (see Section 2.4.6) as mechanisms for providing the digital twins with live data and performing what-if scenarios to facilitate the evaluation of approaches.

The testing framework should acknowledge the need for testbeds with a range of scope, for example, lab bench tests as well as field tests in representative environments, indoor as well as outdoor propagation environments, and integration and evaluation of disparate components as well as full-system experimentation.

The testing framework should aim to include persistent test and evaluation capability in which researchers and solution providers can test, evaluate, and demonstrate capabilities to allow for iterative testing and enable researchers and solution providers to share data and form collaborations to achieve desired integrated capabilities.

3.4 Processes

The following accelerators are activities to be performed jointly by the R&D community and sponsors.

3.4.1 Spectrum TRL Pipeline Review

Priority accelerator

The Technology Readiness Level (TRL) pipeline is the collection of R&D infrastructure available to advance new technologies and solutions through all TRLs from early-stage research to wide deployment, including the evaluation mechanisms used by stakeholders to approve advancement at each stage. The community should periodically assess the overall TRL pipeline to identify gaps or bottlenecks and to prioritize the most impactful limitations.

The periodic review should consider researchers and developers from academic R&D, small business R&D, large enterprises, and federal agencies. Each has different requirements. All should have the ability to progress technologies through the TRLs.

3.4.2 Spectrum Accelerator Workshops

When a particular tool or infrastructure area is identified as a key limitation for spectrum R&D, the community should come together in a workshop format to identify key requirements on a solution and to provide input on prioritization for key investments.

3.4.3 Accelerator Access Resource Mechanism

A mechanism to support access by small research teams to key simulators, testbeds, and other tools and facilities would encourage and democratize use of these R&D accelerators. This mechanism would speed progress by enabling researchers with good ideas to pursue them more quickly. The community and sponsors should come together, potentially in a workshop format, to identify and prioritize opportunities and needs for an Accelerator Access Resource Mechanism.

Part 4: Organization of Spectrum R&D

Achieving the goals of R&D investment in the key innovation areas, and other desired outcomes in this Plan, requires improvements in the structure and process of spectrum R&D, as well as methods to increase coordinated investment toward a whole-of-government and whole-of-nation approach to spectrum challenges.

4.1 Top Priorities

The full list of spectrum R&D organizational improvements was informed by interagency consultation and public input submitted in response to an RFI. Each organizational improvement is described in more detail in the listed section number. The unordered priorities below represent a subset of the full list and are a consolidation of priorities recommended by federal agencies.

- Researcher Rotations into Regulatory Organizations (4.2.1)
- Focused Research to Inform Regulatory Decisions (4.2.2)
- Band Studies as Transition Opportunities (4.2.5)
- Spectrum Engineering Task Force (4.3.1)

4.2 Structure and Process Improvements

The following are key opportunities to improve the organization of spectrum R&D toward more effective R&D investments and smoother transition of innovations from laboratory to deployment.

4.2.1 Researcher Rotations into Regulatory Organizations

Priority organizational improvement

Spectrum R&D would benefit from opportunities for researcher rotations into regulatory organizations from federal and non-federal R&D organizations.

Work experience embedded in a regulatory organization is an excellent way for R&D community members to grasp the challenges of spectrum innovation, and to identify problems where research investment may be productive.

Regulatory organizations will benefit from subject matter expertise, insights into the current state of the art, and informal continuing education of regulatory staff. Regulatory organizations will also gain a better understanding of mission agency constraints and future evolution when they host rotators from federal agencies. For non-federal rotators, possible organizational models include temporary employment, e.g., under the Intergovernmental Personnel Act, collaborative research and development agreements in which researchers embed within the regulatory organization, and internships for graduate students.

Mutual learning opportunities include enhanced understanding of how spectrum innovations transition into practice or deployment, and better description of use cases that should drive future technical and policy development.

4.2.2 Focused Research to Inform Regulatory Decisions

Priority organizational improvement

Spectrum R&D would benefit from short- and medium-term R&D investigations in response to regulatory needs.

These investigations will become collaboration mechanisms that focus academic and private-sector research, and workforce development efforts, on questions or problems identified by the government to inform future regulatory actions.

Potential topics for focused research include technical questions about interference, coexistence, and modeling challenges; collection and analysis of trusted data sets; and how these technical issues affect potential regulatory rules.

New collaboration mechanisms should be informed by successes and lessons learned from past collaborations. One example is the National Advanced Spectrum and Communications Test Network (NASCTN). NASCTN is a multi-agency-chartered partnership that provides a neutral forum for addressing spectrum-sharing challenges in an effort to accelerate the deployment of wireless technologies among commercial and federal users.

4.2.3 Annual Conference on Spectrum Innovation Transition

Spectrum R&D would benefit from a conference series bringing together researchers, industry, and regulators to facilitate transition of spectrum innovations to practice. The conferences should:

- offer an opportunity for innovators to demonstrate working technology to regulators and investors;
- highlight spectrum science results, which often require simultaneous interest from regulators and commercial users to progress toward commercialization and deployment; and
- highlight wireless communications, networking, and sensor innovations that require spectrum regulatory change to be deployed/practiced.

4.2.4 Hands-On Events for Policy Decision Makers

Spectrum R&D would benefit from periodic events, which may be at testbed sites or be remotely accessible, to help regulators and policy makers understand the nature and implications of new spectrum technologies.

4.2.5 Band Studies as Transition Opportunities

Priority organizational improvement

Spectrum R&D would benefit if federal agencies evaluate the benefit of spectrum innovations for band-specific and system-specific needs during or before conducting band repurposing studies. This process leverages the focused attention created by a band study and the investment in upgrades that follows a successful auction as methods to enhance the transition of spectrum innovations to practice. Such research should be:

- targeted toward national spectrum sharing objectives;
- performed early enough that potential innovations can be exploited in contributions to the band study;
- guided by internal mission knowledge of the agencies; and
- aligned with overall goals for evidence-based decision making.

4.2.6 Encourage Researcher Participation in Standards Development

Spectrum R&D would benefit from support for researcher engagement in standardization activities, where this assists with transition of spectrum innovations to practice.

Possible approaches include establishing an annual award to a researcher for important contributions to standards that enhance U.S. national strength or economic welfare. Such awards help the careers of young researchers, who otherwise have little motivation to participate in activities that do not result in traditional scientific publications.

This organizational initiative aligns with the Implementation Plan of the National Standards Strategy for Critical and Emerging Technology (NSSCET), which calls for removing barriers to participation by taking, among other actions, the following: "Provide opportunities for funding that targets the participation of underrepresented stakeholders, including… academia."[9]

4.3 Coordination Initiatives

The broad scope of activities necessary for innovation in spectrum R&D creates a need for coordination and collaboration. Opportunities to promote coordination and collaboration include: (1) metrics to communicate value, (2) mechanisms for idea exchange, and (3) methods for harvesting knowledge. A set of commonly used metrics provide the foundation for communication of the value of different spectrum technologies and are thus important to facilitate meaningful collaboration. Similarly, fostering broad collaboration requires some means to share data, results, and methods. Finally, the development of methods to harvest knowledge from experimentation and experience underpins the content exchanged at such events or on sharing platforms. The following concrete initiatives realize this general framework.

4.3.1 Spectrum Engineering Task Force

Priority organizational improvement

Spectrum R&D would benefit from establishing a technical group to facilitate pre-standards collaboration on, and agreement on selection of standards for, protocols for spectrum information exchange and data representations, sensitive information protection methods/guidance, architecture and open interfaces in the spectrum ecosystem.

4.3.2 Interchange Meetings on Modeling, Simulation, and Testbeds

Organize periodic meetings that promote interaction between the modeling, simulation, and testbed communities. The goal is to work toward common standards, federated experiment support, tool sharing, experiment mobility and joint experimentation between M&S and field testbeds, and collective action in other fora where common equities are impacted.

4.3.3 R&D Roadmaps in Focused Areas

Identify areas where multi-stakeholder R&D roadmaps would enable stakeholders to invest more strategically. Convene meetings or working groups to create those roadmaps.

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[9] The White House. 2024. *U.S. National Standards Strategy for Critical and Emerging Technologies*. https://www.whitehouse.gov/wp-content/uploads/2024/07/USG-NSSCET_Implementation_Rdmap_v7_23.pdf

4.3.4 Classified Collaboration Laboratory

Consider creating a laboratory for collaborative research on classified topics related to spectrum sharing between federal and non-federal users. Include federal and non-federal stakeholder organizations as ongoing, long-term participants to build mutual understanding and accelerate agreement on effective solutions.

4.3.5 International Collaboration Facilitators

Consider identifying one or more entities (e.g., federal agency or industry consortium) as a facilitator for each important international bilateral R&D collaboration. This approach would include establishing mechanisms for private and public entities to inform the facilitators about opportunities and needs, and to learn about partner country activities from the facilitators.

4.4 Workforce Development Initiatives

Rapid advancements in spectrum create the need for a spectrum workforce with the necessary skills to innovate across current and emerging technologies. The U.S. government must better understand workforce needs and take steps to develop and support spectrum talent, with the goal of creating a sustainable spectrum workforce for government, academia, and industry. Moreover, the spectrum pipeline needs to be complemented by those in other disciplinary areas that also contribute to spectrum innovation, such as the social and behavioral sciences, economics, and systems engineering.

Pillar 4 of the National Spectrum Strategy calls for "expanded spectrum expertise and elevated national awareness."[10] It further states that, "[b]ecause a whole-of-government approach is necessary, the U.S. Government will develop and periodically update a National Spectrum Workforce Plan to prioritize the development of, and enhancements to, the spectrum ecosystem workforce."

This Plan does not address the workforce development outcomes specified in Pillar 4; however, it does recognize that a qualified, well-trained U.S. spectrum workforce is essential for the achievement of this Plan's goals and objectives. The United States would benefit from making spectrum research accessible to a wide range of Americans. Moreover, exposing students at all levels, starting at the primary and secondary levels, to spectrum and data science prepares them for successful integration into a world where spectrum availability and efficient use are key drivers of the U.S. economy and industry.

Pursuant to the development of a spectrum workforce to tackle the nation's most challenging spectrum issues, partnerships among government, academia, and industry must be cultivated. These partnerships should prioritize creating courses that are equitably available and accessible to all, and collaborations that facilitate access to educational and research opportunities for students and lifelong learners. Additionally, Grand Challenges for worker training and retraining programs and systems should be explored.

Multidisciplinary education across diverse fields can be beneficial for ensuring fair and equitable access to spectrum information, opportunity, new and emerging technologies, and the development of a diverse marketplace of ideas around technology use and development. Moreover, spectrum awareness must be developed and managed from a holistic perspective that integrates knowledge from various

[10] The White House. 2023. *National Spectrum Strategy*. https://www.whitehouse.gov/wp-content/uploads/2023/11/National-Spectrum-Strategy.pdf

disciplines and backgrounds to foster an interdisciplinary and transdisciplinary approach that considers the needs of all Americans. As such, hiring for spectrum-related disciplines should emphasize diversity from academic, professional, and experiential perspectives.

To facilitate this approach, federal researchers should leverage their unique position and perspective to spearhead research into the roles and impacts of different areas of study on the realities and future of spectrum. As a result, researchers will understand how to engage diverse perspectives and align their efforts and resources with national needs and priorities, as well as across all sectors.

These actions should be taken in addition to other efforts to increase the diversity of communities, identities, races, ethnicities, backgrounds, abilities, cultures, and beliefs involved in spectrum R&D. The federal research community should prioritize research on the best way to increase demographic and cultural representation in the U.S. spectrum workforce. Federal agencies should consider academic partnerships leveraging stipends, paid internship opportunities, and Pathways hiring opportunities for recent graduates.

Finally, educating leaders and staff of private-sector and higher education institutions, and the public about the United States' spectrum workforce needs and priorities is a critical step toward achieving the multi-disciplinary workforce required to create the long-lasting impacts envisioned in this Plan.

Spotlight 4.1: Guidance for Spectrum Workforce Development in the 2023 National Spectrum Strategy

NSS Strategic Objective 4.1 | Attract, train, and grow the current and next-generation spectrum workforce.

> All stakeholders […] must have a spectrum workforce with the necessary skills to innovate across current and emerging technologies.
>
> The U.S. Government will take actions to attract and prepare a well-trained U.S. workforce to meet today's needs and prepare for a rapidly evolving wireless environment.
>
> Innovation is a key to successful national economic growth and spectrum access in support of critical Federal missions.
>
> The Government will publish a national-level workforce plan and work to ensure the Federal careers series offer the right skills and compensation needed for a high-performing spectrum workforce.
>
> Further, the Government will educate decision-makers about spectrum and spectrum-related issues and will increase overall public awareness of the important role that spectrum plays in their lives.

4.5 Public-Private Partnerships

The challenges and opportunities of public-private partnerships in Spectrum R&D are similar to those arising in other technical fields. The following recommendations are closely aligned with those made in the prior NSTC report "National Artificial Intelligence R&D Strategic Plan 2023 Update."[11]

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[11] Select Committee on Artificial Intelligence of the National Science and Technology Council. 2023. *National Artificial Intelligence Research and Development Strategic Plan 2023 Update*.https://www.nitrd.gov/pubs/National-Artificial-Intelligence-Research-and-Development-Strategic-Plan-2023-Update.pdf

American leadership in science and engineering research and innovation is rooted in the U.S. government-university-industry R&D ecosystem. As the American Academy of Arts and Sciences has written, "America's standing as an innovation leader" relies on "establishing a more robust national Government-University-Industry research partnership."[12]

Over the last several decades, fundamental research in information technology conducted at universities with federal funding, as well as in industry, has led to new multibillion-dollar sectors of the Nation's economy. Concurrent advances across government, academia, and industry have been mutually reinforcing and have led to innovative, vibrant wireless and spectrum technology.

The general objectives and specific ideas described below associated with the application of public-private partnerships should be considered for specific actions to be made part of the Spectrum R&D actionable 5-year plan when this Plan is revised. The accelerators described in Part 3 and Grand Challenges to be added in the revision are both areas that might best be achieved through public-private partnerships.

4.5.1 Achieving More from Public-Private Partnership Synergies

By leveraging resources, including facilities, datasets, and expertise, the strategists and participants in public-private partnerships will more rapidly advance science and engineering innovations. For example, sharing spectrum measurement artifacts, models, data, and results serves to reduce resource use and redundancies. Similarly, government-university-industry R&D partnerships bring pressing, real-world challenges faced by industry to university researchers, enabling use-inspired research, and leveraging industry expertise to accelerate the translation of open and published research results into viable products and services in the marketplace for economic growth. Public-private partnerships are especially well served when they build on joint engagements among federal agencies that enable collaboration and better return on investment in areas where agencies' missions intersect. The multi-agency-chartered partnership model, e.g., the National Advanced Spectrum and Communications Test Network (NASCTN), could be utilized to foster engagement across federal agencies, industry, and academia.

Expansion and extension of multiple types of programs that provide opportunities for researchers from government, academia, and industry to spend time working in another sector would additionally enable federal funding agencies, academia, and the private sector to work more effectively with one another. The unique perspectives and capabilities of each sector enable mutual benefit. Industry's commercialization and scale-up of spectrum-dependent systems is assisted by universities' early-stage R&D and federal laboratories' focused materials, device, and measurement research, and specialized computing resources.

4.5.2 Improving Mechanisms for R&D Partnerships

R&D is a team effort, often conducted by diverse groups operating in multiple institutions. Public-private partnerships require institutional arrangements to facilitate the pooling of resources for efficient return on investment of time and funding, faster outcomes, and positive impacts, and avoiding duplication of efforts. An array of potential configurations and mechanisms for public-private

[12] American Academy of Arts and Sciences. 2014. *Restoring the Foundation*. https://www.amacad.org/multimedia/pdfs/publications/researchpapersmonographs/AmericanAcad_RestoringtheFoundation_Brief.pdf

partnerships has been developed over the past few decades. Expanding the reach of existing mechanisms, improving their functioning and outputs for a more diverse set of participants and application spaces, and creating new forms of public-private partnerships are significant and valuable endeavors. Examples include the following:

- **Individual project-based collaborations**. In these partnerships, government agencies pool resources and/or expertise with industry, nongovernmental organizations, foundations, and academics to address a critical issue, such as safety and trustworthiness. This process is a flexible and rapid approach, but often challenging to sustain and expand. Models include Cooperative Research and Development Agreements and other transaction authorities (e.g., the National Spectrum Consortium). The NSF Resilient & Intelligent NextG Systems program is an example of an individual project-based collaboration where 9 companies and 3 agencies pooled resources to support research in resilient networking.
- **Joint programs to advance open, precompetitive, fundamental research**. Government has traditionally played a critical role in supporting foundational research through grants and contracts (primarily at universities), for which there is no short-term commercial application, but instead advances the field as a whole.[13] Given the massive need for expanded fundamental and use-inspired research, innovative methods to bring private-sector resources to these ends are critical. Obtaining such resources is often challenging, in part due to the short project timescales typical of profit-driven companies. One example that addresses this challenge is the NSF Industry-University Cooperative Research Centers program,[14] which provides an NSF-supported institutional framework for industry to support precompetitive research at universities. In general, non-federal partners contributing research resources can receive intellectual property rights as governed by the Bayh-Dole Act.[15]
- **Collaborations to deploy and enhance research infrastructure**. Large-scale spectrum-related research will require significant research infrastructure, including testbeds and compute and storage resources. Joint projects between the government and private-sector partners can achieve economies of scale that enable access to necessary resources for all engaged parties. Equitably providing such resources to a large segment of stakeholders is critical to maximizing the impact of such collaborations. One example of a collaboration to deploy and enhance research infrastructure through a public-private partnership is the NSF Platforms for Advanced Wireless Research (PAWR) program.
- **Collaborations to enhance workforce development, including broadening participation**. While there are many programs to encourage students to enter science, technology, engineering, and mathematics (STEM) fields, public-private partnerships should explore opportunities to pool resources to broaden the overall pipeline of spectrum-related R&D skills.

[13] National Academies of Sciences, Engineering, and Medicine. 2020. *Information Technology Innovation: Resurgence, Confluence, and Continuing Impact*. The National Academies Press. https://nap.nationalacademies.org/catalog/25961/information-technology-innovation-resurgence-confluence-and-continuing-impact

[14] National Science Foundation. *Industry-University Cooperative Research Centers Program (IUCRC)*. 2020. https://new.nsf.gov/funding/opportunities/industry-university-cooperative-research-centers

[15] *U.S.C. Title 35 - PATENTS.* (n.d.). https://www.govinfo.gov/content/pkg/USCODE-2011-title35/html/USCODE-2011-title35-partII-chap18.htm

New types of partnerships for curriculum development and new approaches to developing and implementing curricular standards for programs could be especially impactful by building broader capacity for spectrum science and management education and training.

- **Federal challenges and prize competitions**. According to the Congressional Research Service, "…prize competitions benefit the federal government by allowing federal agencies to (1) pay only for success; (2) establish ambitious goals and shift technological and other risks to prize participants; (3) increase the number and diversity of individuals, organizations, and teams tackling a problem, including those who have not previously received federal funding; (4) increase cost effectiveness, stimulate private-sector investment, and maximize the return on taxpayer dollars; and (5) motivate and inspire the public to tackle scientific, technical, and societal problems."[16]
- **Data and model sharing**. Creating partnerships with the goal of sharing data and testbeds at scale could make a big difference in the breadth of availability of cutting-edge simulations to model spectrum-dependent systems and propagation channels.

In each case, leveraging each partner's strengths for the benefit of all is vitally important to achieving the greatest impact.

[16] *Federal Prize Competitions*, Congressional Research Service, 2020 https://crsreports.congress.gov/product/pdf/R/R45271

Part 5: Index of Spectrum R&D Opportunities

Part 6: Glossary

Accepted Interference: Interference at a higher level than defined as permissible interference and which has been agreed upon between two or more administrations without prejudice to other administrations.[17]

Active System: A radiocommunication system operating in an active (transmitting) radiocommunication service.

Coexistence: The state of two or more radio devices or networks existing at the same time and at the same place in a shared spectrum space.[18]

Cognitive Radio: A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.[19]

Critical Infrastructure: Assets, systems, and networks, whether physical or virtual, that are considered so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof.[20]

Critical System: In the context of this Plan, is a spectrum-dependent system that requires high availability to support critical missions including safety-of-life, protection of property, disaster prevention and recovery, law enforcement, national security, or other missions of similar importance and defined priority.

Digital Twin: A set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin.[21]

Dynamic Access Method: Refers to a rule or control system for spectrum access that depends on external conditions (for example, an “if-then” statement to be executed at runtime).

Dynamic Spectrum Sharing: Adaptive coexistence using techniques that enable multiple electromagnetic spectrum users to operate on the same frequencies in the same geographic area without causing harmful interference to other users (in cases where such users have an expectation of protection from harmful interference) by using capabilities that can adjust and optimize

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[17] ITU-R Radio Regulations, Chapter 1. https://www.itu.int/pub/R-REG-RR/en

[18] IEEE. 2019. *IEEE Standard for Definitions and Concepts for Dynamic Spectrum Access: Terminology Relating to Emerging Wireless Networks, System Functionality, and Spectrum Management*. https://ieeexplore.ieee.org/servlet/opac?punumber=8694193

[19] Report ITU-R SM.2152-0, *Definitions of Software Defined Radio (SDR) and Cognitive Radio System (CRS).* https://www.itu.int/pub/R-REP-SM.2152

[20] CISA, Critical Infrastructure Sectors. https://www.cisa.gov/topics/critical-infrastructure-security-and-resilience/critical-infrastructure-sectors

[21] National Academies of Sciences, Engineering, and Medicine. 2024. *Foundational Research Gaps and Future Directions for Digital Twins*. The National Academies Press. https://nap.nationalacademies.org/catalog/26894/foundational-research-gaps-and-future-directions-for-digital-twins

electromagnetic spectrum usage in real time or near-real time, consistent with defined regulations and policies for a particular spectrum band.

Electromagnetic Spectrum Management: The technical and regulatory process and function for bringing order to the use of the limited electromagnetic spectrum.

Emission: Radiation produced, or the production of radiation, by a radio transmitting station. Note: For example, the energy radiated by the local oscillator of a radio receiver would not be an emission but a radiation.[22]

Fast interference management: Activities and processes executed to enhance electromagnetic compatibility and prevent, prepare for, respond to, and recover from electromagnetic interference, on a timescale rapid enough to protect real-world and/or machine-speed activities.[23]

Grand Challenge: A Grand Challenge is an articulation of a desired objective that focuses attention and resources on specific, well-defined problems and promotes innovative approaches, processes and solutions to solving them. The Grand Challenge approach does not define an immediately obvious solution. [24]

Harmful Interference: Interference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with [the ITU] Radio Regulations.[25]

Interference: The effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radiocommunication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy.[26]

Intermodulation (IM): Intermodulation is created when signals from two or more transmitters mix in a nonlinear device. A "nonlinear device" could be an amplifier, a power supply, or even the junction of two dissimilar metals that behave as a diode. When signals mix, they produce additional signals (IM products) on new frequencies that are mathematically related to the original frequencies.[27]

National Security: Those activities which are directly concerned with the foreign relations of the United States, or protection of the Nation from internal subversion, foreign aggression, or terrorism.[28]

Out-of-band Emission: Emission on a frequency or frequencies immediately outside the necessary bandwidth which results from the modulation process but excluding spurious emissions.[29]

Passive System: A radiocommunication system operating in a passive (receive-only) radiocommunication service.

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[22] ITU-R Radio Regulations, Chapter 1. https://www.itu.int/pub/R-REG-RR/en

[23] Chapin J., 2022. *Fast Interference Management* 2022, URL: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4184007

[24] *Use of Grand Challenges in the Federal Government***,** V. Peña, C.A. Stokes, IDA Science and Technology Policy Institute, 2019

[25] ITU-R Radio Regulations, Chapter 1. https://www.itu.int/pub/R-REG-RR/en

[26] ITU-R Radio Regulations, Chapter 1. https://www.itu.int/pub/R-REG-RR/en

[27] Joint Staff. 2019. *Joint Electromagnetic Spectrum Management Operations in the Electromagnetic Operational Environment*. https://www.jcs.mil/Portals/36/Documents/Library/Manuals/CJCSM%203320.01C.pdf

[28] Code of Federal Regulations. 5 CFR 1400.102. https://www.ecfr.gov/current/title-5/part-1400/section-1400.102#p-1400.102(a)(3)

[29] ITU-R Radio Regulations, Chapter 1. https://www.itu.int/pub/R-REG-RR/en

Permissible Interference: Observed or predicted interference which complies with quantitative interference and sharing criteria contained in these [ITU Radio] Regulations or in ITU-R Recommendations or in special agreements as provided for in these Regulations.[30]

Radio Frequency Spectrum: In general, the portion of the electromagnetic spectrum subject to national and international radiocommunication regulations. The Convention of the International Telecommunication Union defines this as frequencies "arbitrarily below 3000 GHz".[31]

RF Waveform: The simple (single frequency) or complex (modulated/multiple frequency combination) radio frequency output of a transmitter, as generated, evaluated, or defined in the time domain.

Safety Service: Any radiocommunication service used permanently or temporarily for the safeguarding of human life and property.[32]

Spectrum-Dependent Systems: An electronic system, subsystem, or device that depends on transmission or reception in the electromagnetic spectrum to properly accomplish its functions.

Spectrum Digital Twin: A digital twin for observables of interest in the electromagnetic spectrum.

Spectrum Sharing: The application of technical methods and operational procedures to permit multiple users to coexist in a shared spectrum space.[33]

Spurious emission/harmonic: Emission on a frequency or frequencies which are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products, but exclude out-of-band emissions.[34]

Unwanted Emission: Consist of spurious emissions and out-of-band emissions.[35]

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[30] ITU-R Radio Regulations, Chapter 1. https://www.itu.int/pub/R-REG-RR/en

[31] International Telecommunication Union. 2022. *Collection of the Basic Texts of the International Telecommunication Union adopted by the Plenipotentiary Conference*. https://www.itu.int/en/publications/gs/Pages/publications.aspx?lang=en&media=electronic&parent=S-CONF-PLEN-2022

[32] ITU-R Radio Regulations, Chapter 1. https://www.itu.int/pub/R-REG-RR/en

[33] IEEE. 2019. *IEEE Standard for Definitions and Concepts for Dynamic Spectrum Access: Terminology Relating to Emerging Wireless Networks, System Functionality, and Spectrum Management*. https://ieeexplore.ieee.org/servlet/opac?punumber=8694193

[34] ITU-R Radio Regulations, Chapter 1. https://www.itu.int/pub/R-REG-RR/en

[35] ITU-R Radio Regulations, Chapter 1. https://www.itu.int/pub/R-REG-RR/en

Part 7: References

7.1 Key Federal Wireless Spectrum R&D References

These federal wireless spectrum R&D reference documents informed the WSRD subcommittee in the preparation of this Plan.

1. NextG Communications Research and Development Gaps Report, https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1293.pdf
2. Advanced Wireless Test Platforms Team Information Request Report, https://www.nitrd.gov/pubs/AWTP-Info-Request-Report-2022.pdf
3. Artificial Intelligence & Wireless Spectrum: Opportunities and Challenges. 2020 Workshop Report, https://www.nitrd.gov/pubs/AI-WirelessSpectrum-2019WorkshopReport.pdf
4. Research and Development Priorities for American Leadership in Wireless Communications, https://www.nitrd.gov/pubs/Research-and-Development-Priorities-for-American-Leadership-in-Wireless-Communications-Report-May-2019.pdf
5. WSRD Radio Receiver Systems: R&D Innovation Needs and Impacts on Technology and Policy: Workshop Summary, https://www.nitrd.gov/pubs/WSRD-Radio-Receiver-Workshop-Report-2018.pdf
6. Wireless Spectrum Sharing: Enforcement Frameworks, Technology, and R&D, https://www.nitrd.gov/pubs/WSRD_VIII_Workshop_Report.pdf
7. Federal-Commercial Spectrum Sharing Workshop: Models, Applications, and Impacts of Incentives for Sharing, https://www.nitrd.gov/pubs/WSRD_Workshop_VII_Report.pdf
8. Federal - Commercial Spectrum Data: Understanding Information Exchange Needs, Issues, and Approaches, https://www.nitrd.gov/pubs/WSRD_Workshop_VI_Report.pdf
9. Understanding the Spectrum Environment: Data and Monitoring to Improve Spectrum Utilization, https://www.nitrd.gov/pubs/WSRD_Workshop_V_Report.pdf
10. Promoting Economic Efficiency in Spectrum Use: the economic and policy research agenda, https://www.nitrd.gov/pubs/WSRD_Workshop_IV_Report.pdf
11. Next Generation Spectrum Sharing Technologies Workshop on Federal Government Investments in Innovative Spectrum-Sharing Techno, https://www.nitrd.gov/pubs/WSRD_Workshop_III_Report.pdf
12. Federal Government and Private Sector Collaboration on Research Development, Experimentation, and Testing of Innovative Spectrum Sharing Technologies, https://www.nitrd.gov/pubs/WSRD_Workshop_II_Report.pdf
13. Toward Innovative Spectrum Sharing Technologies: A Technical Workshop On Coordinating Federal Government/Private Sector R&D Investment, https://www.nitrd.gov/pubs/WSRD_Workshop_I_Report.pdf

7.2 Other Important Federal References Impacting Spectrum R&D

1. Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook) | National Telecommunications and Information Administration, https://www.ntia.gov/publications/redbook-manual

2. Telecommunications Act of 1996 | Federal Communications Commission, https://www.fcc.gov/general/telecommunications-act-1996
3. Communications Act of 1934: as amended by Telecom Act of 1996, https://transition.fcc.gov/Reports/1934new.pdf

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