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Request for Information on the National Spectrum Research and Development Plan

The MITRE Corporation

MITRE's Response to the OSTP RFI on Spectrum R&D

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About MITRE

MITRE is a not-for-profit company that works in the public interest to tackle difficult problems that challenge the safety, stability, security, and well-being of our nation. We operate multiple federally funded research and development centers (FFRDCs), participate in public-private partnerships across national security and civilian agency missions, and maintain an independent technology research program in areas such as artificial intelligence, intuitive data science, quantum information science, health informatics, policy and economic expertise, trustworthy autonomy, cyber threat sharing, and cyber resilience. MITRE's ~10,000 employees work in the public interest to solve problems for a safer world, with scientific integrity being fundamental to our existence. We are prohibited from lobbying, do not develop or sell products, have no owners or shareholders, and do not compete with industry—allowing MITRE's efforts to be truly objective and data-driven. Our multidisciplinary teams (including engineers, scientists, data analysts, economists, organizational change specialists, policy professionals, and more) thus dig into problems from all angles, with no political or commercial pressures to influence our decision making, technical findings, or policy recommendations.

MITRE's spectrum-focused activities are organized into three categories:

- In our role supporting federal agencies through FFRDCs, we offer critical assistance to both military and civilian agencies in managing and utilizing the electromagnetic spectrum.
- Through our public-private collaboration efforts, we work towards overcoming USG-Industry spectrum negotiation/coexistence challenges. This includes addressing issues such as potential impacts to GPS signals from in-band cellular emissions and possible interference to Radio Altimeters from 5G cellular in the 3.7-3.98 GHz band.
- Our independent research focuses on emerging technology and innovation, economic analysis, impact and risk analysis, policy and regulation, and acquisition support.

MITRE's spectrum goal is to help create whole-of-nation spectrum solutions that balance the critical spectrum needs of competing stakeholders while meeting national goals of next generation wireless technology deployment across the United States.

Introduction and Overarching Comments

Spectrum, a critical and scarce resource, plays a pivotal role in various aspects of national security, economic prosperity, and individual connectivity. It is utilized to protect the nation, perform fundamental scientific research, and enable safety in aviation and other means of transportation. Moreover, it stimulates commerce by providing ready access to the internet and serves as a fundamental resource for communication used by millions of Americans. The importance of spectrum necessitates a comprehensive and effective National Spectrum Research and Development Plan (R&D Plan) to manage its use and development efficiently. The following sections provide detailed insights and recommendations on the approach, objectives, and priorities for this R&D Plan.

Take a Strategic Approach to the R&D Plan

A National Spectrum R&D Plan should have two ends in mind: supporting the National Spectrum Strategy and ensuring advancement of spectrum capabilities necessary to ensure future national security and economic prosperity. To ensure both are accomplished, MITRE recommends taking a comprehensive approach to crafting this R&D Plan by using a strategic planning framework that is consistent with the Government Performance and Results Act.[1] This R&D Plan must also reach beyond the National Science and Technology Council's (NSTC) normal focus of federal R&D coordination to maximize needed collaboration with nongovernmental organizations.

If we assume that the vision for this R&D Plan is meeting the two ends proscribed above, a draft set of high-level goals that collectively meet this vision would be:

- Goal 1: Develop new technology for improved spectrum awareness.
- Goal 2: Create actionable tools/technologies that identify/enable opportunities for spectrum coexistence, data analysis, and dynamic sharing, through collaborative R&D (both nationally and internationally), researcher user facilities, and leveraging advanced sensing technologies and artificial intelligence and machine learning (AI/ML) techniques.
- Goal 3: Enhance spectrum management infrastructure and policy development.

The R&D Plan should identify priority objectives to meet each goal, and then assign agency actions to meet each objective. Doing so helps ensure the strategic comprehensiveness of the R&D Plan so that it meets the government's vision and provides the Executive Office of the President (EOP) an ability to measure and track progress.

Systemic Overview and Assumptions for Spectrum R&D Prioritization

Setting priorities for spectrum R&D requires a top-down systems perspective of the desired functionality. An operational view, like Figure 1, showcases a large-scale cellular network coexisting with various USG assets across regions. Consistent with the National Spectrum Strategy's aim to maximize technology use for spectrum sharing, we assume that spectrum sharing gives priority to systems that depend on or are enabled by the spectrum in a specific region to perform their tasks over a certain time. The sharing arrangement, which could be exclusive or cooperative, may vary based on time, location, or frequency.[2]

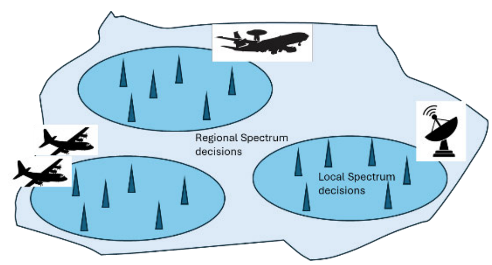

Figure 1 - Operational View (OV-1) of Spectrum Sharing

Figure 2 provides a more detailed view of the activities within the regions depicted in Figure 1, offering a deeper understanding of the complexity of an advanced sharing system. This figure presents a functional block diagram, indicating the presence of various entities within the region, without specifying their exact physical locations.

[1] D. Blackburn. Effective EOP Leadership – Learned Guidance for an Incoming Appointee. 2024. MITRE, https://www.mitre.org/sites/default/files/2024-02/Effective%20EOP%20Leadership-2_AM508.pdf. P5.

[2] Alternatively, employing techniques such as orthogonal polarization, modulation, and coding schemes can enable truly simultaneous use of the spectrum where time, space, and frequency boundaries are not necessarily needed; such schemes are likely of little near-term value given the lack of flexibility in existing USG programs of record that are expensive and difficult to modify.

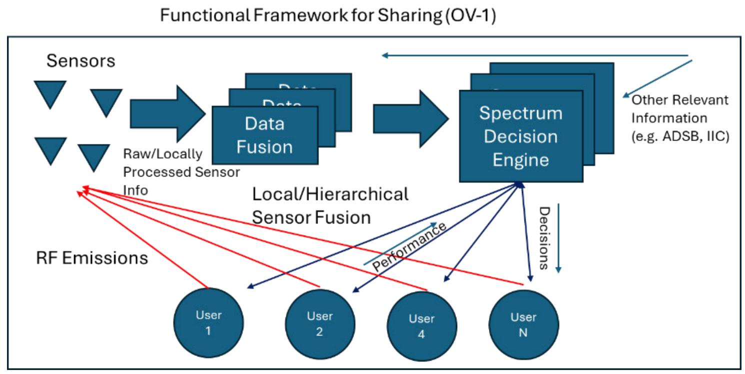

Figure 2 - Functional Block Diagram of Regional Spectrum Sharing

The intent of Figure 2 is to illustrate a notional computational cycle of a spectrum sharing system. In this cycle, radio frequency (RF) information is sensed, digitally processed, and combined with other relevant information to facilitate spectrum decisions. This information is passed to a decision engine, which may also receive additional data and which predictively schedules spectrum decisions that are disseminated to entities within the region. RF emissions from these entities are subsequently sensed as the spectrum situation continues to evolve.

The elements of Figure 2, along with consideration for their physical placement, highlight some of the research priorities that should be addressed and prioritized. These specific priorities, in relation to this figure, are discussed in more detail in subsequent sections of this document.

Evaluation Mechanisms and Technology Maturation

In the diverse field of spectrum research, prioritizing activities based on the stages of technology maturation is crucial. To facilitate this, MITRE recommends incorporating specific evaluation and maturation mechanisms, as illustrated in Figure 3.

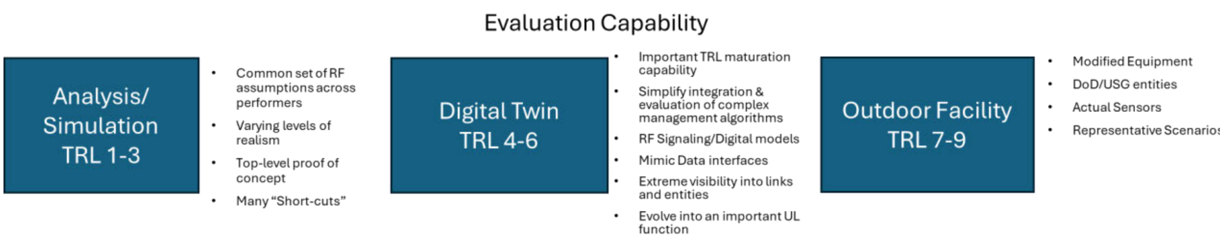

Figure 3 - Readiness Tiers of Evaluation

Modeling & Simulation (M&S) for Coexistence Analysis (Technology Readiness Level [TRL] 1-3)

R&D initiatives should focus on establishing a set of acceptable methodologies, M&S tools, propagation models, and geographic information system datasets to maximize potential alignment at the conclusion of studies. Additionally, the strategy should consider the possibility of centralizing an evaluation capability for M&S, where feasible.

Digital Twins for Spectrum Sensing/Sharing (TRL 4-6)

Digital twins accurately emulate real site topology data for federal and commercial users, providing precise digital representations of propagation environments.

As concepts mature, costs increase, but efficiencies can be realized by creating testbeds for comparing various techniques. The most significant return is likely at the mid-TRL range, where decisions transition a concept into a detailed design phase. Digital twins offer unique insights into new concepts' performance at scale, without the need for detailed design or physical prototyping.

Testbeds and digital twins are crucial tools in spectrum research and development, forming key components of a cooperative R&D infrastructure. They provide a controlled, adaptable environment for simulating and emulating interactions between different systems in a spectrum sharing scenario. This supports the evaluation of various spectrum sharing strategies and algorithms, enabling a comprehensive understanding of the algorithms' impact across all stakeholders.

These tools foster national collaboration across government, industry, non-profit organizations, and academia, aligning with Pillar Two of the National Spectrum Strategy (Strategy).[3] They facilitate agreement on metrics, methods, models, and solutions, providing a common platform for diverse stakeholders to work toward shared objectives. This is in line with the Strategy's call for a persistent strategic spectrum planning process guided by the best available science and data (Strategic Objective 2.1).

By accurately replicating real-world conditions, digital twins enable the use and analysis of extensive and shared data, promoting data-driven decision making. This is a key aspect of the Strategy's approach to improving spectrum efficiency and bolstering coexistence by facilitating investments in new and emerging technologies (Strategic Objective 3.1).

Outdoor Test Facility (TRL 7-9)

While the main spectrum sharing testbed may be hosted by the National Telecommunications and Information Administration (NTIA) Institute for Telecommunication Sciences (ITS), a federated virtualized approach is necessary to connect other testbeds to it. For example, the National Science Foundation (NSF) funded SpectrumX testbed and the Department of Defense (DoD)-funded Playas testbed should have the capability to interface directly with the NTIA testbed. These testbeds play a crucial role in facilitating the testing and validation of new sensing technologies, data analytics, sharing, and coordination protocols over large geographic scales. They should provide a realistic environment for spectrum sensing, encompassing both urban and rural settings, and be accessible to researchers from government, industry, and academia.

International Collaboration

Although not a test facility per se, the importance of international collaboration in this context is paramount. An advanced sharing system in the US may yield economic benefits domestically. However, the approach to collaboration with international partners, particularly as it pertains to the DoD, is critical. If not handled appropriately, it could potentially jeopardize unimpaired DoD access to certain spectrum.

Beyond R&D

The task of designing a new sharing system that optimizes spectrum utility for all stakeholders is daunting, and it is important to consider future implications. In a free market, numerous capable commercial entities may propose products that purport to comply with the interfaces, standards, and principles established by this R&D effort. Given the complexity of this solution, and the crucial role of spectrum for stakeholders, it will be essential to establish a function akin to an Underwriters Laboratory. This would subject all proposed solutions to rigorous testing. Given the complex interactions involved, such exhaustive testing is warranted.

[3] National Spectrum Strategy. 2023. The White House, https://www.ntia.gov/sites/default/files/publications/national_spectrum_strategy_final.pdf.

Answers to Questions Posed in the RFI

1. Recommendations on strategies for conducting spectrum research in a manner that minimizes unnecessary duplication, ensures that all essential spectrum research areas are sufficiently explored, and achieves measurable advancements in state-of-the-art spectrum science and engineering.

There is recognition that advancing critical and emerging technologies within the context of modern international science and technology (S&T) competition will require greater collaboration.[4,5] A recent MITRE analysis[6] also shows that providing additional resources and enabling specific public-private collaboration *at the right time and with the right focus* within the technology lifecycle can rapidly accelerate S&T development and its application across a variety of use cases. This analysis uncovered that there are four points (or "levers") within a technology development process where coordinated attention across the public and private sectors will yield greater return on investment and accelerate S&T innovation and adoption compared to generally targeted collaborations pursued historically, as illustrated in Figure 4.

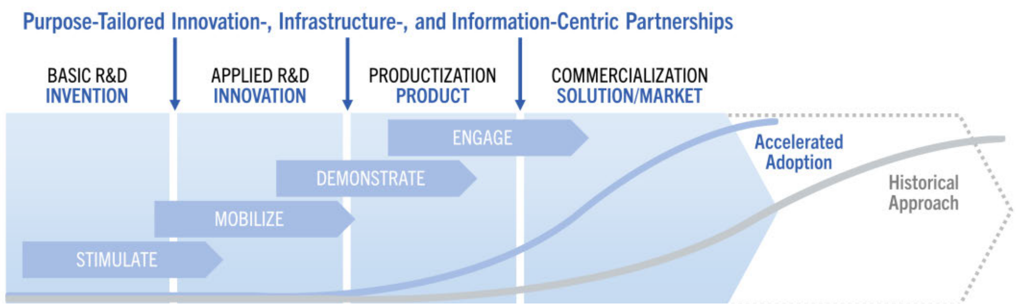

Figure 4 - Strategic Collaboration at Four Levers in a Technology's Evolution Can Accelerate Its Adoption

Applying this lever concept to spectrum R&D produces the following suggestions for activities and incentive structures:

- Lever 1: Stimulating Research and Creating Interest
  - Establishing Public-Private Partnerships: Encourage partnerships between government agencies, academia, and the private sector to jointly fund and conduct early-stage spectrum research. This can leverage the strengths of each sector and increase overall investment in spectrum R&D.
  - Developing Innovation Clusters: Establish a nationwide facility for spectrum research to serve as a centralized hub for collaboration among various stakeholders. This facility could become a geographic concentration of interconnected businesses, suppliers, and associated institutions in the field of spectrum research.

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[4] C. Ford et al. A "Horizon Strategy" Framework for Science and Technology Policy. 2021. MITRE, https://www.mitre.org/sites/default/files/2021-11/prs-21-1440-horizon-strategy-framework-science-technology-policy.pdf.

[5] Platforms Interim Panel Report. 2022. Special Competitive Studies Project, https://www.scsp.ai/wp-content/uploads/2023/01/Platforms-Panel-IPR.pdf.

[6] D. Blackburn et al. Partnerships to Accelerate Advancement of Priority S&T. 2023. MITRE, https://www.mitre.org/news-insights/publication/partnerships-accelerate-advancement-priority-st.

- Lever 2: Mobilizing a Network (Active Ecosystem)
  - Creating an R&D Consortia: Establish a network that brings together spectrum researchers, investors, and end users to exchange information. Foster collaboration to create a sense of shared ownership and commitment, thereby leading to increased investment.
  - Lowering the "Cost of Entry": Explore capabilities that provide researchers with access to facilities and data necessary for their work. Making existing resources available for use would lower the "cost of entry" for participating entities, allowing them to focus on their specific research interests without the burden of creating their own infrastructure. This approach could stimulate more investment in spectrum R&D by making it more accessible and cost-effective for a wider range of researchers.
- Lever 3: Demonstrating Impactful Solutions
  - Implementing Co-funding Mechanisms: Encourage partnerships between government agencies, academia, and the private sector to jointly fund and conduct research. This can leverage the strengths of each sector and increase overall investment in spectrum R&D.
  - Enhancing Awareness of Research Activities: Regularly disseminate information about ongoing research findings and technological advancements to enhance awareness among public and private sectors. This broad awareness supports follow-on research and technology commercialization, fostering a vibrant ecosystem of innovation. In addition, this continuous flow of information can inform updates to the R&D Plan, ensuring that future investments are targeted to the most-needed areas, thereby maintaining the plan's relevance and continuing to attract investment from all stakeholders.
- Lever 4: Increasing Business/Industry Engagement
  - Establishing Clear Goals and Metrics: Set clear and measurable objectives for this latter-stage R&D, and track progress toward these goals to ensure that investment in R&D is targeted and effective.
  - Equipping Potential Users with Knowledge on the Commercial Market: The Spectrum R&D Plan should direct investments to agencies' spectrum R&D offices to either internally or externally contract research in state-of-the-art spectrum sensing and sharing capabilities to support future mission spectrum requirements. With increased awareness, agencies will come into these studies more willing to consider dynamic coexistence solutions.

2. Recommended priority areas for spectrum research and development, as well as productive directions for advancing the state-of-the-art in those areas.

The following sections highlight specific research areas that ought to be undertaken to meet the objectives of the National Spectrum Strategy.

Spectrum Awareness: Supporting and enabling spectrum awareness[7] and spectrum coexistence[8] should be a fundamental aspect within the R&D Plan. As a critical enabler for dynamic spectrum

[7] Spectrum awareness implies the availability of specific information necessary to make optimal decisions related to spectrum management. Information includes but is not limited to understanding the current spectrum utilization, efficiency, availability, and potential interference within a current region and across diverse geographical locations and time. The full suite of information to meet the definition of this term will be fleshed out through the research proposed.

[8] Spectrum coexistence refers to the ability to have more than one system and/or stakeholder utilize the same band.

access, efficient spectrum utilization, and interference mitigation, spectrum awareness forms the backbone of modern spectrum management strategies. This effort should aim to quantify, in mathematical terms, the intuitive concepts prevalent in this domain wherever feasible. However, achieving comprehensive spectrum awareness, both on a national scale and within the "Decision Engines" of Figure 2, presents significant technical and operational challenges. These challenges range from the development of advanced sensing technologies and analytics for real-time spectrum monitoring to the establishment of protocols for data sharing and coordination among a diverse range of spectrum stakeholders, including federal agencies, commercial entities, and academia.

<u>A Comprehensive System-Engineered Framework for Sharing/Dynamic Spectrum Access</u>: Research should aim to develop a comprehensive framework that includes acceptable mechanisms for data sharing, data analytics, data collection from advanced sensing technologies, and management of spectrum coexistence in various potential approaches. Extensive R&D is needed to evaluate, refine, and mature the approaches under consideration for implementation. These solutions either will drive or must align with a more refined version of Figure 2. A top-down system engineering approach is necessary to ensure that all components are clearly defined and understood, eliminating any "black box" scenarios.

<u>Improving Economic and Policy Drivers and Their Influence on Technical Requirements</u>: R&D efforts should investigate the influence of economic incentives and policy on stakeholder decisions regarding spectrum efficiency, access, and innovation. This includes understanding how these factors shape the development and deployment of spectrum technologies and their adaptation for new uses. Research insights can guide the creation of new economic models and policy frameworks to achieve national spectrum goals.

Unique spectrum considerations for the USG include the need to test electronic warfare without impacting non-military spectrum allocations and understanding the effects of evolving cellular technology (5G/6G) on USG incumbents. Future missions related to homeland security, aviation, and ground transportation also require specific attention. Solutions should balance the spectrum needs of the USG and other stakeholders.

Spectrum management operates under evolving rules and policies. The system should be designed to interpret these policies and translate them into algorithmically actionable information. For instance, spectrum resilience and assured access are critical for certain mission applications and passive scientific observation.

A balanced set of quantifiable target metrics is crucial for a common discourse on spectrum issues. While spectrum utilization efficiency is important, it shouldn't overshadow other metrics like national security, transportation safety, or economic efficiency. These metrics can guide spectrum decisions and inform the modernization of practices/algorithms to enhance spectrum use for all stakeholders.

<u>Implementing Technology and an Algorithmic Framework for Overall Spectrum Sharing</u>: The ultimate technological goal is to align the sharing mechanism's operation with the operational timescales of individual systems to optimize access. Given the small timescales of cellular operation (e.g., 0.5 ms in Mid-Band), practical issues like latency in information transmission and processing are crucial to the sharing system's timing budget. These constraints direct research toward decentralized systems for local decision making, predictive systems, and systems with control aspects operating at different timescales as latency allows.

It's also important to consider decision making with only partial information, as achieving "Full Spectrum Awareness" even within a region may be unattainable in the short term. Therefore, a robust R&D plan should acknowledge the practical and fundamental limitations of the achievable information level. Specific functions from Figure 2 are detailed below:

- Advanced Spectrum Sensing Technologies: R&D should focus on advanced sensing technologies, including quantum sensing, that can provide real-time, accurate, and high-resolution data on spectrum usage across diverse frequency bands and geographical locations. This includes the development of cost-effective, scalable, and robust spectrum sensors that can be distributed nationwide.
- Data Analytics and Artificial Intelligence: The vast amount of data generated by spectrum sensors requires processing and analysis to extract meaningful insights about spectrum usage and availability. R&D should concentrate on advanced data analytics, machine learning, and artificial intelligence techniques that can process and analyze spectrum data in real time, detect patterns of spectrum usage, predict future spectrum availability, and identify potential interference.
- Spectrum Data Sharing and Coordination: Achieving national spectrum awareness requires effective coordination and data sharing among diverse spectrum stakeholders. R&D should aim to develop secure, scalable, and efficient protocols for spectrum data sharing and coordination, including privacy-preserving data sharing protocols. This includes creating common data formats and interfaces for spectrum data exchange, as well as protocols for collaborative decision making in dynamic spectrum access.
- Dynamic Spectrum Access and Management: Research should focus on improving the management of dynamic spectrum access and use. This includes exploring how information about managing prospective interference might be reported and what the operations security concerns are. Key characteristics include:
  - Automatic and Rapid Mitigation of Interference Problems: This needs to be a priority, with research being a collaborative effort between government, for interference requirements, and commercial entities, led by the latter as they will need to implement interference mitigation techniques at scale and prove they are meeting interference thresholds.
  - Decision Making with Partial or Imperfect Information: While total spectrum awareness should be the ultimate goal, it is unachievable in the near term. Therefore, R&D is also needed to support decision making based on partial or imperfect information. This includes the development of robust decision-making algorithms and models that can handle uncertainty and incomplete data.
  - Decentralized Spectrum Management: Given the vast scale and complexity of the spectrum environment, a decentralized approach to spectrum management is necessary. This means that decisions need to be made somewhat locally, based on the spectrum data available in a specific geographical area or "footprint." R&D is needed to develop effective methods and protocols for decentralized spectrum management, such as game-theoretic, blockchain, or market-based approaches.
  - Federated Solutions: Given the predictive nature of spectrum solutions, there exists a class of solutions where localized decision making can be informed or augmented centrally with known information such as a platform's mission plan, or via AI/ML updates to processing engines that learn from previous decisions and consequences.

- Cybersecurity in Spectrum Technologies: As spectrum-dependent technologies continue to evolve and become more integrated into our daily lives and critical infrastructure, the need for robust cybersecurity measures becomes increasingly paramount. R&D efforts should focus on developing secure spectrum access technologies and encryption methods for spectrum data. This includes researching potential cybersecurity threats specific to wireless technologies and developing proactive measures to mitigate these threats. It is also important to consider the security implications of spectrum sharing and dynamic spectrum access, ensuring these technologies are designed with security in mind from the ground up.
- User Experience Research: While the technical and engineering aspects of spectrum use are crucial, understanding the end-user experience is equally important for the successful implementation and acceptance of new technologies. R&D efforts should focus on studying user behavior, needs, and acceptance of new spectrum technologies and services. This includes researching how different spectrum-dependent technologies are used in various contexts (e.g., home, work, public spaces), how users interact with these technologies, and what barriers or challenges they face. The insights gained from this research can inform the design and development of user-friendly, accessible, and inclusive spectrum technologies.
- Assessment and Certification of Advanced Systems: Research should also focus on the assessment and certification of advanced systems. This would involve developing standards and procedures for evaluating the performance and reliability of new spectrum technologies and systems.

3. Recommendations on grand challenge problems for spectrum R&D. Grand challenges are selected research problems that if attacked will help motivate and coalesce R&D efforts.

A decentralized approach to spectrum management is essential, allowing decisions to be made locally based on the spectrum data available in a specific geographical area or "footprint." A valuable grand challenge that could inform solutions in this area would be the outdoor proof-of-concept implementation of a dynamic sharing scenario. This scenario would involve a two-tier decentralized decision-making solution, where local decisions are made for nodes grouped in clusters by proximity, with coordination across clusters for regional-level decisions.

MITRE further recommends a risk-informed spectrum analytic approach be adopted to provide more granular information, including quantification of the likelihood and impact of adverse effects, such as harmful interference, to support decision makers in minimizing interference risk and maximizing spectrum utilization.[9]

4. Recommendations on spectrum R&D accelerators

The use of digital twins, as previously discussed, is a relevant and viable accelerator for the spectrum R&D process. Another strategy to expedite the process is to employ parallel workstreams. For example, as a testbed is being developed, stakeholders and industry should engage in forums to define use cases of interest, outline specifications for proof-of-concept activities, and plan early pilot implementations. This approach ensures that when technologies

[9] "Commerce Spectrum Management Advisory Committee (CSMAC) Report of Subcommittee on Electromagnetic Compatibility Improvements," CSMAC, December 19, 2023. Robert Henry and Harris Zebrowitz, "Risk-Informed Spectrum Sharing and Management Capability," The MITRE Corporation, ISART 2022.

and solutions become available, workstreams can converge for a faster outcome, thus reducing the time from research to implementation.

6. Recommendations on a process to refine and enhance the R&D plan on an ongoing basis

The R&D Plan must be continuously refined and enhanced to keep pace with the rapidly evolving field of spectrum science and engineering. A structured and systematic process for updating the plan ensures its relevance, effectiveness, and alignment with the latest advancements and research activities. This process should involve regular reporting from agencies, consistent analysis of new studies, routine review and update of the plan, and feedback from stakeholders. The following recommendations outline a process for refining and enhancing the R&D plan on an ongoing basis.

Coordinated Reporting Process: Establish a coordinated process for agencies to report updates on their respective spectrum research. This process should involve regular reporting intervals and a standardized format for reporting to ensure consistency and ease of comparison across different agencies' reports. The collected information should be used to update the R&D plan, ensuring it reflects the most recent advancements and ongoing research activities.

Regular Analysis of New Studies: The R&D Plan should consistently analyze and incorporate new International Telecommunications Union coexistence and other spectrum studies. This involves setting up a dedicated team or mechanism to regularly review these studies, extract relevant findings, and update the R&D Plan accordingly. This ensures that the plan remains up to date with the latest global advancements in spectrum science and engineering.

Regular Review and Update of the R&D Plan: The R&D Plan should be reviewed and updated on a regular basis, such as annually or biannually. This review should consider the progress made toward the plan's objectives, the effectiveness of the strategies employed, and any changes in the spectrum research landscape. The review findings should be used to refine the plan, adjusting objectives, strategies, and priorities as necessary.

Stakeholder Feedback: Seek feedback from stakeholders, including non-federal entities such as industry and academia, on the R&D Plan. This feedback can provide valuable insights into the plan's effectiveness and areas for improvement. The feedback should be considered in the regular review and update of the R&D Plan.

7. Terminology and definitions relevant for spectrum R&D.

Dynamic Spectrum Sharing (DSS), a focus but undefined phrase in the Strategy, is a set of technologies that allow wireless systems to adaptively share spectrum resources. DSS makes real-time adjustments to spectrum use based on changing conditions like user demand or interference levels. The goal of DSS is to enhance spectrum efficiency and flexibility, supporting various applications and services. By dynamically sharing spectrum, DSS aims to maximize spectrum utilization, accommodate more users, and improve wireless service performance and reliability.

Spectrum awareness, while intuitively important both nationally and at each decision-making point (e.g., the decision engines of Figure 2), needs to be defined in a quantifiable manner.