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Toward Practical Federal Spectrum Sharing for Advanced Wireless Technologies

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***Abstract*—Wireless communications have become critical to modern society as the foundation of vital services, business interactions, and social connections. As technology develops and new scenarios emerge, wireless communications become increasingly entrenched as a foundation for modern life. The materialization of 5G has been especially impactful as an enabler for a wide range of new scenarios and increased dependence. With increasing demand for wireless communications comes increasing demand for the radio frequency (RF) spectrum necessary to support these communications. This spectrum demand, largely driven by desire to realize ubiquitous 5G networks, both public and private, is currently driving a reconsideration of spectrum assignments and forcing legacy users of spectrum to update their use of spectrum. As one of the largest legacy users of spectrum, the U.S. Government (USG) is particularly impacted by the increasing demand for spectrum for non USG use. Unfortunately, there is no clear pathway for U.S. federal agencies to modernize their spectrum use and instead these agencies are forced to simply react to spectrum repurposing driven by overwhelming demand. Here we present preliminary work toward a roadmap for federal agencies to modernize their spectrum use through practical analysis and leveraging emerging spectrum sharing (SS) technologies. This effort utilizes the example of DOE spectrum use in the context of National Telecommunications and Information Administration (NTIA) and Federal Communications Commission (FCC) repurposing to examine the factors that must be considered to facilitate spectrum sharing by federal agencies. Furthermore, this work provides an initial survey of the SS models and SS technologies of highest relevance to federal use. We particularly examine the emerging capabilities of 5G itself to enable SS and unlicensed access through transformative capabilities such as new radio unlicensed (NR-U). This work is a step toward translating the large body of academic discussion on SS into a practical roadmap for federal agencies.**

***Index Terms*—spectrum sharing, sharing models, FCC, NTIA, national spectrum strategy, federal, 5G**

I. Introduction

Radio frequency (RF) spectrum has become an unquestionably critical foundation for modern life. President Biden states that ”Radio frequency spectrum is among our Nation’s most important national resource” in [1]. The recent National Spectrum Strategy opens by stating ”Radio frequency spectrum plays a significant — but often unacknowledged — role in Americans’ daily lives” [2]. Indeed, RF spectrum already underpins a significant portion of the economy and this impact is only expected to grow [3] [4]. As a result, the management of spectrum has recently become a topic of interest at the highest levels of government.

Given our utter dependence on RF spectrum, President Biden has stated that the U.S. must develop a strategy to make this resource broadly available by modernizing spectrum management and planning [1]. In response, National Telecommunications and Information Administration (NTIA) has assembled the National Spectrum Strategy with a focus on improving the national framework around spectrum policy with the stated goal of working toward dynamic spectrum sharing (SS) [2]. This strategy exemplifies an increased attention on spectrum innovation from the highest levels of government which reflects both the critical importance of RF spectrum and the need to update spectrum management and use. Given the importance of spectrum, changes to spectrum use are likely to have broad reaching impacts and force widespread reconsideration of operations that depend on spectrum.

Federal agencies are likely to acutely feel the impact of changes to spectrum management and use. Both President Biden and the National Spectrum Strategy highlight the ”diverse missions of the Federal Government” [1] which depend on multifaceted use of spectrum [2]. This broad diversity of spectrum use, often consisting of a large number of one-off scenarios, creates challenges simply for ongoing spectrum operations. Significant changes in spectrum management and use are likely to impact different scenarios differently, necessitating significant effort to ensure that critical functions remain operational. In large part, the need to change spectrum management and use is driven by significant pressure to repurpose spectrum allocated to federal agencies to facilitate the expansion of commercial spectrum use. Simultaneously, federal agencies are also feeling the effects of the expanded capabilities of wireless systems which drive a need for more spectrum access. Therefore, federal agencies, already challenged by a broad variety of unique spectrum scenarios, are feeling pressure to support an increasing set of critical wireless functions while simultaneously decreasing the amount spectrum dedicated to federal use.

A. Spectrum Repurposing

To facilitate the rollout of the transformational 5G cellular networks, spectrum authorities worldwide have allocated new spectrum in mmWave or reallocated spectrum in sub-6 GHz. New spectrum was largely available in the mmWave bands since 5G is the first cellular technology to use it, although there are a few existing non-cellular systems even in this frequency range. Sub-6 GHz spectrum, on the other hand, were mostly already allocated either commercially (Federal Communications Commission (FCC)) or federally (NTIA) in U.S. As a result, spectrum repurposing efforts in the U.S. have sought to make more spectrum available for 5G as well as other advanced wireless technologies such as Wi-Fi 6E.

In February 2021, FCC finalized the assignment of 280 MHz, in the range 3.7-3.98 GHz, for licensed use. Licenses for this spectrum were distributed via an auction with total winning bids reaching over $81 billion. Incumbents in this band were moved to the upper 200 MHz of the C band (4-4.2 GHz) with 20 MHz of guard band in 3.98-4 GHz. This was followed by another historic auction of flexible-use licenses to 100 MHz in 3.45-3.55 GHz raising more than $22 billion in January 2022. These flexible-use licenses herald a shift toward focusing on cooperative spectrum sharing as a means of using spectrum more efficiently. In this regard, 5G is poised to accelerate the efficiency of spectrum use through its innovative capability to operate with only shared or unlicensed spectrum. Notably, this capability does not require any associated licensed spectrum initiated actions. Thus 5G provides the means to increase spectrum efficiency through repurposing bands previously allocated to U.S. Government (USG) entities such as the Department of Energy (DOE) or Department of Defense (DoD).

Perhaps most significantly for future repurposing, the recently released National Spectrum Strategy has identified 2,790 MHz to be studied for shared use [2]. The strategy motivates these studies by noting that dynamic spectrum is critical to meeting the demand for spectrum driven by 5G and other modern technologies. Overall, this document represents a whole of USG perspective with support from the highest levels and its focus on spectrum sharing marks significant recognition of this approach. The bands identified within this document are therefore likely to be considered the highest priority bands for SS. Table I provides these bands.

TABLE I
NATIONAL SPECTRUM STRATEGY TARGETED BANDS (FREQUENCIES IN MHZ)

Lower Edge	Upper Edge	Width	Center
3100	3450	350	3275
5030	5091	61	5060.5
7125	8400	1275	7762.5
18100	18600	500	18350
37000	37600	600	37300

II. PATH FORWARD

The National Spectrum Strategy calls for a ”spectrum pipeline” to facilitate efficient and effective spectrum repurposing that can enable innovative new uses and meet growing demand [2]. The strategy notes that the foundation of this pipeline should be based in strategic and systematic evaluation of spectrum and spectrum use. Further discussion of spectrum evaluation in the strategy envisions a collaboration between federal agencies and the NTIA. Federal agencies will be expected to bring an understanding of (1) their current spectrum holdings, (2) current and future spectrum-dependent operations, and (3) operational requirements to the envisioned collaborative evaluation. The strategy anticipates that this information will enable a federal agency to specify the efficiency of their operations in terms of spectrum use and how their operational performance depends on spectrum. Further, federal agencies would benefit from an awareness of the potential for improving their spectrum efficiency and mission effectiveness through the use of advanced technology. As such, the National Spectrum Strategy implies a set of requirements for federal agencies to effectively participate in the envisioned approach to spectrum management.

Federal agencies have a significant role in the emerging paradigm for spectrum management established by the National Spectrum Strategy. This role has clear responsibilities as discussed above that necessitate some targeted study on the part of federal agencies themselves. That is, federal agencies will need to (1) clearly characterize their own spectrum holdings, (2) assess the requirements that these holdings seek to address, (3) determine the impact of anticipated repurposing, and (4) identify the emerging technologies best suited to mitigate any negative impacts. Federal agencies will likely be called upon to rapidly implement modern approaches to spectrum use that leverage the rapid development of wireless technology and support the expected growth in spectrum demand. Therefore federal agencies will have to select the most promising technologies for their specific use cases and develop practical experience with these through testing and solution prototyping. Overall, these spectrum analysis efforts must be accomplished with a focus toward modernizing spectrum use and together constitute an agency specific spectrum pipeline that echoes the broader pipeline envisioned in the National Spectrum Strategy. Given the ongoing evolution of spectrum management, realizing these agency specific pipelines encapsulates the agency specific requirements for effective spectrum stewardship.

III. DOE SPECTRUM CASE STUDY

Here we examined the recent activities of DOE as instructive example of the agency specific pipeline discussed above. The DOE Office of the Chief Information Officer (OCIO) has funded the Idaho National Laboratory (INL) to assure DOE spectrum-dependent operations by leveraging emerging dynamic sharing technologies for real world DOE use cases. This effort is separated into three phases. Phase 1 comprises a comprehensive research, engineering study, and technology evaluation program. This phase has two interrelated objectives: (1) evaluate the likely impact of ongoing spectrum repurposing on DOE, and (2) identify opportunities to leverage advanced wireless technologies, such as 5G, to support DOE SS. Phase 2 focuses on practical test and evaluation to develop a data-driven understanding of the obstacles to SS for DOE. Phase 3 develops toward a prototype SS solution for DOE by validating the most promising SS solutions across high priority DOE use cases. To date, this effort is nearing the end of Phase 1,

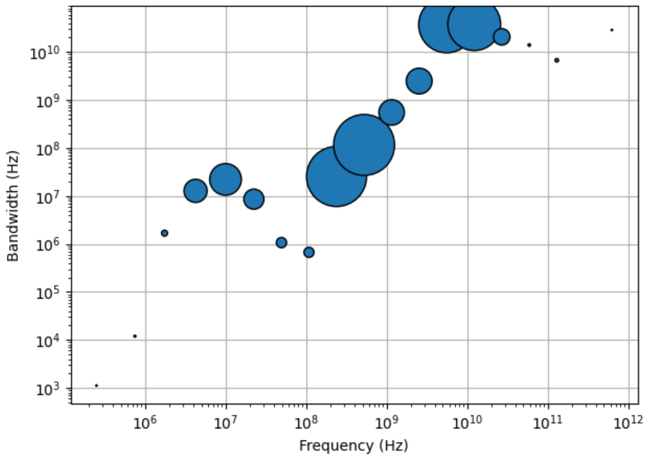

Fig. 1. Summary of DOE assignments

which directly provides the strategic and systematic spectrum evaluation called for in National Spectrum Strategy. Below we summarize the activities of this phase as an illustration of the emerging responsibilities of federal agencies in the paradigm for spectrum management envisioned by the National Spectrum Strategy.

A. Analysis of Spectrum Holdings

The first step of the agency pipeline focuses on the characterization of a federal agency's spectrum holdings. The best source for information about a federal agency's holdings is the NTIA data base. INL has collected all DOE assignments from this database and reviewed their use to outline current DOE spectrum use. This database records 7,715 DOE assignments that span all U.S. states and territories and total more than 149 GHz of total spectrum. Figure 1 summarizes these assignments. In this figure, the y-axis displays the total spectrum assigned at each frequency and the size of mark indicates the number of assignments within a given frequency range.

DOE defines nine communication functions that outline the operational use of spectrum use. These functions include: (1) NAVAIDS/TTS[1], (2) Long-Distance Communication, (3) LMR-Communication[2], (4) Satellite Communications, (5) Telemetry, (6) Microwave, (7) Counter-UAS[3], (8) Experimental, and (9) Contingency. Considering both the number of assignments and associated assigned bandwidth, the primary communications functions supported by DOE assignments are: (1) Experimental, (2) Contingency, (3) Microwave, (4) LMR-Communications, and (5) Telemetry.

B. Assessing Spectrum Impacts and Opportunities

While the communications functions above help to outline the operational use of spectrum for DOE, they do not provide a consistent picture of the technical requirements. Understanding these technical requirements underpins an understanding of the spectrum use that enables a first order assessment of both the modern technologies that could be employed and the potential to leverage shared spectrum. To facilitate this type of analysis, INL has defined a set metrics that can outline the technical requirements for DOE systems: (1) latency, (2) jitter, (3) reliability (rel.), (4) range, and (5) goodput (GP). INL then used these metrics to define 12 requirement groups that capture the various ways in which DOE uses spectrum. The relationship between metrics and requirement groups is shown in Table II. This table provides the sensitivity of each requirement group to each of the metrics. The sensitivity is scored on a 5 point scale, where 1 indicates that the requirement group can handle below average performance for a given metric, 3 indicates a need for an average level of performance, and 5 indicates a need for above average performance. These scores are intended only for comparison between groups and not as a generalized statement of performance requirements.

TABLE II
SENSITIVITY OF EACH REQUIREMENT GROUP TO METRIC PERFORMANCE

	Latency	**Jitter**	**Rel.**	**Range**	**GP**
Alarm	3	1	5	2	1
Backhaul	3	3	3	4	4
Beacon	2	4	4	3	1
Control	4	3	5	3	3
Data	1	1	2	3	4
Machine	5	4	5	2	2
PTN[4]	3	5	4	4	1
Radar	4	4	4	4	1
SATCOM	2	2	2	5	2
Sensor	3	4	4	3	3
Video	3	2	4	3	3
Voice	3	2	4	3	2

The identified requirement groups provide a high level picture of the technical priorities for DOE spectrum use. Considering both the number of assignments and the amount of assigned spectrum, the primary requirement groups for DOE are (1) control (42% of assignments/37% of spectrum), (2) radar (1% of assignments/41% of spectrum), (3) voice (35% of assignments/2% of spectrum), and (4) data (13% of assignments/6% of spectrum).

This set of priorities enables a first order assessment of the opportunity to for DOE to benefit from the technologies driving repurposing, rather than simply reacting to the repurposing itself. Given that 5G is a major driver of the ongoing spectrum repurposing, INL has so far focused its assessment on the potential for DOE to leverage 5G. Approximately 69% of DOE assignments, accounting for 76% of DOE assigned spectrum, overlaps with spectrum relevant to 5G (300 MHz to 80 GHz). This overlap indicates that 5G is likely to significantly

[3]NAVAIDS/TTS: Navigational aids/Time to station
[3]LMR: Land Mobile Radio
[3]UAS: Unmanned Aerial System

[4]PTN: Position, Timing, and Navigation

impact DOE spectrum use even if DOE does not directly leverage the technology. At the same time, the capabilities of 5G appear to potentially match the needs of 9 of the 12 requirement groups for DOE spectrum use. Only the beacon, radar, and sensor groups depend on the use of specialized signals or equipment that fall outside of the scope of 5G. Of course, actually implementing 5G for any given DOE use would require additional assessment and consideration of the associated costs, but there appears to be value in further investigation of the application of 5G to DOE operations.

Simultaneously, the first order assessment of technical priorities provides an initial picture of the potential impact of spectrum repurposing on DOE. Focusing on the spectrum targeted with the National Spectrum Strategy, approximately 28% of DOE assignments accounting for 44% of spectrum assigned to DOE is likely to be affected by spectrum repurposing. Over 99% of these assignments, accounting for 77% of this spectrum, fails into the 7125 - 8400 MHz range. There is no frequency within this range that doesn't overlap with at least 1 DOE assignment. Within 7125 - 8400 MHz, 89% of DOE assignments fall into the control requirement group, which is particularly sensitive to latency and reliability. As a first order assessment, these systems will require robust protections to effectively operate within a shared spectrum paradigm. Additional research focusing on the specific scenarios of this spectrum use will be required to realize the vision set forth in the National Spectrum Strategy.

IV. Survey of Spectrum Sharing for Federal Use

To facilitate ongoing development of SS solutions for federal agencies, here we present a preliminary survey of SS. In this discussion, we differentiate SS models from SS technologies as each of these represent separate but important considerations for federal agencies. For our purposes we define a SS model as an operational framework that defines the roles and responsibilities of entities involved in SS. SS technologies, on the other hand, are methods to realize sharing among communications systems within the framework of a given model. We note that the nature of federal agencies requires that both the models and technologies employed for SS must (1) address a variety of communications scenarios, (2) exhibit high maturity, and (3) maintain security of operations.

A. Spectrum Sharing Models

SS models significantly impact the realization of SS by defining the expectations and responsibilities for all entities involved in sharing. The model underpining sharing determines (1) whether any given entity should received priority access, (2) the types of protections any given entity should expect, and (3) the mechanisms for resolving any interference between entities. As such, the model employed for sharing significantly impacts the types of communications that can be effectively supported within shared spectrum.

Matinmikko et al. outline the foundation of current SS models in [5]. The authors identify that spectrum sharing policy in the U.S. is largely rooted in the federal Spectrum Access System (SAS), which is a geo-location database system to facilitate three-tiered sharing. These tiers comprise: (1) an incumbent entity, originally conceived as a federal user, that always has priority access and should be protected from interference, (2) priority access licensees which have priority over and protections from third-tier entities, and (3) general authorized access that must obtain a license and avoid impact higher tier entities. The SAS tiers are displayed in Figure 2. The authors also point out that SAS itself is rooted in techniques developed to facilitate the sharing of TV White Space, primarily through geographic isolation. Parvini et al. point out that SAS has subsequently become the foundation of Citizens Broadband Radio Service (CBRS) which now supports deployment of 5G networks without spectrum licenses [6]. FCC has approved the use of a centralized SAS with Environmental Sensing Capability (ESC) to co-ordinate SS in the CBRS band [7]. This geo-location based, three-tier sharing has therefore become the dominate model in U.S. spectrum sharing.

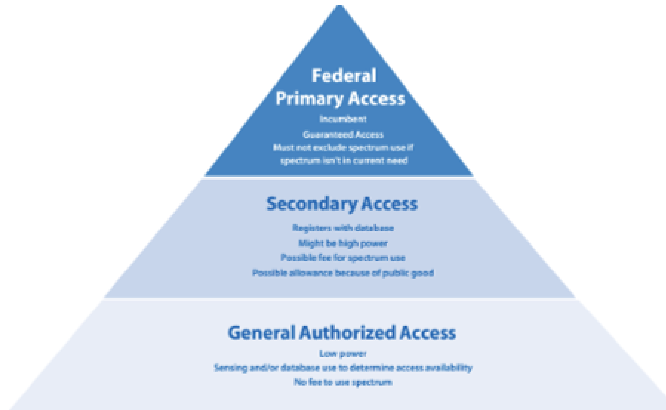

Fig. 2. SAS Tiers from [8]

Of course, the SAS model is not the only option. Parvini et al. also provide a taxonomy of spectrum sharing schemes [6], reproduced in Figure 3. At the highest level this taxonomy distinguishes between licensed access and unlicensed access. The licensed access group is further sub-divided into dynamic spectrum access within a given network and sharing between heterogeneous systems. Sharing between heterogeneous systems is dominated by the SAS model discussed above and the Licensed Shared Access (LSA). LSA is a two-tiered model for sharing between an incumbent entity and licensed secondary users based on rules negotiated between the two groups. The LSA is more established in Europe than the U.S.

Unfortunately, the SAS model has been shown to exhibit some issues in the areas of privacy and security. Grissa et al. show that the databases at the center of SAS expose the private operational data of secondary users [9]. Lin et al. show that incumbent information is also exposed when utilizing the ESC framework [10]. These limitations errode the potential utility of the SAS to federal agencies.

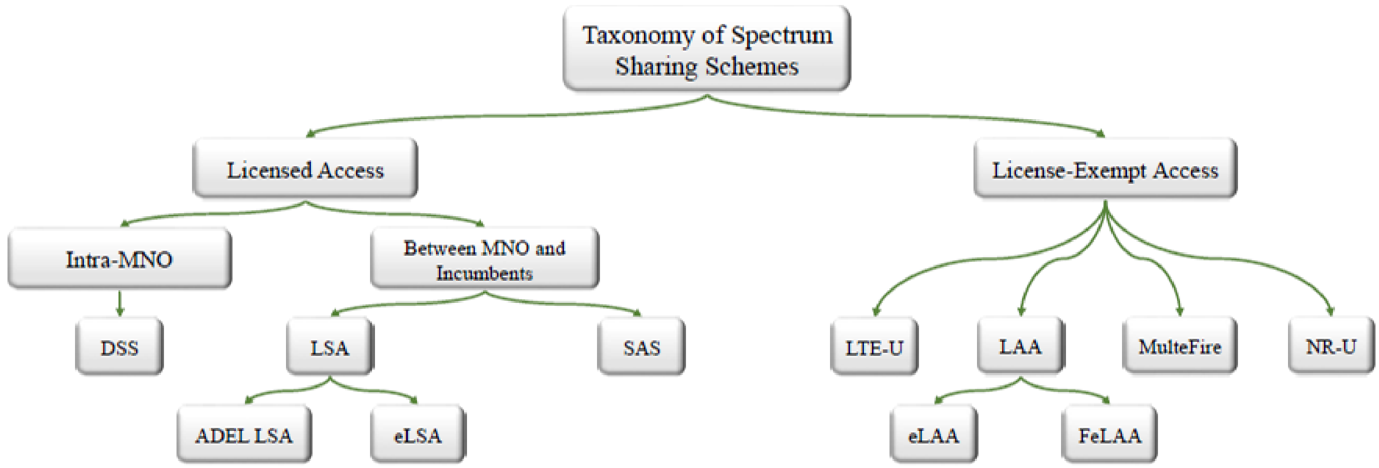

Fig. 3. Spectrum Sharing Scheme Taxonomy from [6]

B. Spectrum Sharing Technologies

Given the prominence of 5G as a modern communications technology, the mature state of 5G technology, and the broad scope of scenarios supported by 5G, we believe that 5G is a leading candidate for federal communication modernization. Additionally, 5G includes several capabilities that support SS, primarily through supporting unlicensed spectrum. The center piece of 5G unlicensed access is new radio unlicensed (NR-U). Therefore we focus our preliminary examination of SS technologies on unlicensed 5G techniques, particularly highlighting NR-U.

NR-U represents a mode of 5G operations tailored to unlicensed spectrum, where SS is assumed and 5G systems must be prepared for premption. The 3GPP outlines a variety of procedures to support this mode of operation in [11]. These procedures have been shown to effectively support sharing with a variety of systems. For example, Daraseliya et al. show that NR-U can effectively share with WiGig technologies in mmWave spectrum in [12]. Hirzallah et al. found that NR-U can be an effective alternative to Wi-Fi in 5 GHz in [13]. Sathya, Kala, and Naidu propose NR-U for supporting small cells in 6 GHz in [14]. Alexandre et al. show that NR-U can efficiently share the 700 MHz band with LTE and narrowband internet of things in [15]. Overall, it is clear that NR-U has significant promise to utilize 5G in SS scenarios.

At the same time, SS is an area of active research and there are several examples that extend the existing capabilities of 5G. Work in [16]–[21] introduced a novel SS scheme where each base station (BS) in multiple 5G networks autonomously share spectrum securely with their user equipment (UE) as sensors (see Figure 4 from [18]). Interference is sensed with carrier sensing at the receiver (CSR) as opposed to carrier sensing at the transmitter (CST). Fair sharing of spectrum is accomplished by the operators with a distributed scheduler at their BSs without any communication among the operators or without the use of a centralized server to facilitate the sharing. The central role of security in this work, exemplified by the removal of a centralized server that contributes to security issues in SAS, makes this effort especially notable for federal agencies. Zhou et al. echo this focus on security by proposing blockchains as a means to facilitate SS for 5G systems in [22]. Alternatively, Bajrachaya, Shrestha, and Jung outline a path toward leveraging NR-U to support future Industry 4.0 use in [23]. Bhattacharjee, Acharya, and Bhattacharya survey the application of cognitive radio techniques for supporting multicasting in 5G networks in [24]. Overall, these examples show that the capabilities of 5G in SS contexts are continuing to expand.

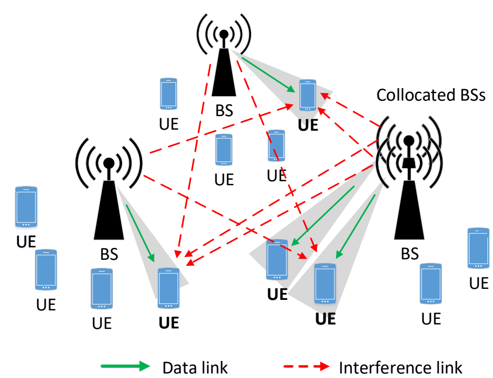

Fig. 4. Spectrum Sharing among multiple 5G networks with co-located BSs and UEs.

V. Summary and Next Steps

Federal agencies will continue to face the challenges of supporting more wireless capability with less dedicated spectrum. As noted by the National Spectrum Strategy, SS is a critical component of supporting the increasingly complicated missions of federal agencies. This work is a preliminary step toward realizing SS for federal agencies. We progress toward SS by providing an initial pathway for a Federal agency spectrum pipline that fits into the national spectrum pipeline envisioned by the National Spectrum Strategy. We illustrate this pathway by discussion of the DOE spectrum use case.

Finally we provide an initial survey of the SS models and technologies relevant to federal agencies. As we continue this work, we intend to expand our survey to provide a more complete resource for federal agencies. Additionally we plan to progress into practical, test based examination of SS solutions for DOE.

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