Testing of Policy-Based Dynamic Spectrum Access Radios

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***Abstract*—Policy-driven Dynamic Spectrum Access (DSA) systems are emerging as one of the key technologies to enable the Department of Defense (DoD) to meet its increasing requirements for access to the electromagnetic spectrum. A key open issue surrounding deployment and continuing development of DSA systems concerns (1) the need to test and evaluate the performance of DSA in avoiding interference to itself and assigned incumbent users and (2) the performance of DSA network in the presence of various types of potential interference. In this paper we describe test framework and concepts to characterize performance of DSA-enabled policy-based radios. Our test framework includes tests to characterize the inherent interference-avoidance characteristics of DSA, such as the time to abandon a channel, as well as tests that address performance implications of a particular DSA policy. The test framework also provides for the ability to inject a relevant electromagnetic environment (EME). The proposed framework is flexible allowing for customization of the relevant test conditions, such as the EME, and facilitates simulation of typical communications events such as network formation and fragmentation.**

***Index Terms*—Dynamic spectrum access, policy based radio, cognitive radio, PBR, DSA, test plan, framework.**

I. Introduction

Dynamic Spectrum Access (DSA) is emerging as one of the key technologies to enable the Department of Defense (DoD) to meet its increasing requirements for access to the electromagnetic spectrum [1], [2]. Policy-based radios (PBRs) with DSA functionality allow for more efficient utilization of the available spectrum in comparison to the traditional spectrum reservation paradigm [3]. Under the spectrum reservation paradigm, radiocommunication systems within a specified area are assigned a static set of frequencies and no other systems are permitted on those frequencies regardless of their actual occupancy. The use of DSA-enabled systems will enable multiple devices to operate in the same slice of spectrum by using a spectrum coexistence mechanism [4]–[7]. In an opportunistic DSA system, the spectrum coexistence mechanism usually involves spectrum sensing to identify unoccupied frequencies prior to transmission. Coexistence for PBR can also be enforced through the use of radio policies that can prohibit transmission in certain areas, at certain times, or on certain frequencies.

DSA represents a promising approach to alleviate the spectrum shortage in the military and civilian environments. However, one of the key issues surrounding deployment and continuing development of DSA systems concerns the need to test and evaluate the performance of DSA in avoiding interference to assigned spectrum users as well as avoiding interference from assigned users to itself and evaluating the performance of DSA network in the presence of various types of potential interference. For example, if an assigned user begins to transmit on frequency occupied by a DSA system, the times required to identify the user, abandon the channel, and reform the network on an alternate channel, are important parameters with respect to interference avoidance and network performance.

In this paper, we establish an extensible test framework to characterize the performance of DSA-enabled PBR networks that provides a baseline for characterization and testing of the emerging DSA technology. We note that the National Telecommunications and Information Administration (NTIA) has released a test plan to address spectrum sharing and coexistence between DSA and legacy systems [8]. While it provides a good baseline for characterization of adjacent channel interference, sensor desensitization, and several other metrics, it does not address network formation, fragmentation, collision, coalescence, and other effects defined in this test plan that are also essential metrics for efficient spectrum sharing. Continuing DSA developments will lead to a more complete framework encompassing the NTIA tests as well as the currently proposed tests.

II. General approach

A. Objective

The goal of developing the DSA test framework is to address testing of features specifically associated with DSA and PBR capabilities. There are already well-established test procedures for various radio characteristics, such as frequency stability or interference immunity [9], [10]. Our approach is to leverage these existing standards and augment them with additional tests to evaluate the performance of DSA specific features. Our proposed framework deals with the radio frequency (RF) aspects of DSA as well as the overall network performance of DSA systems.

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While many of the DSA Network Performance tests in the framework assume a master-slave configuration, the same tests and procedures apply to various architectures. For example, ad-hoc networks typically have a single control node that for test purposes would be the equivalent to a master node. Likewise, for a peer-peer network, an arbitrary node would be considered the master node. In all cases, the DSA Network Performance metrics described will be relevant.

B. Test Procedures

The main purpose of DSA is to deal gracefully with the perturbations in the electromagnetic environment (EME). Our test framework is concerned with the following types of perturbations:

- Appearance of interferer or assigned user on a frequency currently occupied by the DSA PBR
- Change in position, time, or another environmental parameter that changes the policy currently in force
- Increase in propagation (path) loss between two groups of network nodes
- Convergence of network nodes that have been previously separated due to poor path loss between them.

The first two items listed are generic for any DSA PBR. The last two items apply specifically to DSA Mobile Ad-Hoc Networks (MANETs), which are an important subclass of DSA systems. To reproduce these effects in the laboratory, we must force adaption of the DSA network in response to a forced change in EME or policy variable. Thus, we need to perform the following:

1) Configure the DSA system or network
2) Load relevant policies
3) Simulate the background EME
4) Prepare measuring equipment
5) Apply the interference or simulate another EME change, such as position change
6) Measure and record the relevant performance metrics.

Therefore, a DSA test involves an independent selection of the following elements:

- Configuration and size of the DSA network
- Policy in force during the test
- The simulated EME
- Type of interference, e.g. wideband vs. narrowband
- Network locations affected by the interference
- Any other variables that can affect policy decisions, such as position, altitude, etc.

III. Framework Details

A. Single-Network Setup

The specific steps for setting up a DSA network are largely dependent on the manufacturer of the system. However, the general approach to the test should be independent of the PBR type. Fig. 1 illustrates a general test configuration.

The setup in Fig. 1 illustrates testing of a generic N-node network. For networks capable of multiple nodes, we deem a four-node network to be the minimum network size required for the tests, although development of scalability tests will require a greater number of nodes. In the following test descriptions, we assume that the network uses a master-slave configuration. The Master node, which may also be referred to as the Base Station node or head node, is the hub of the network. The slave nodes are the spokes of the network. All network traffic is routed through the master to the intended recipients. While the master-slave configuration is not required to use the test framework, it is important to identify any privileged or control nodes in advance of the test to differentiate interference impacts on these nodes in comparison to "ordinary" nodes.

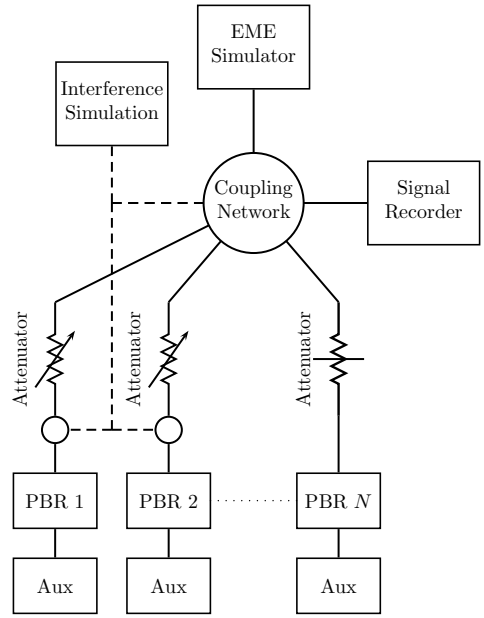

Fig. 1. Single DSA network test configuration.

In addition to the system under test, the essential components of the test circuit are the following:

1) Signal Recorder: The signal recorder must be able to record the radio-frequency signal in real-time across the desired frequency range. It is important to use a device that records the time-domain signal continuously over the required test period, rather than a scanning device that tunes serially across the span.

2) EME Simulator: The EME simulator simulates the background EME. Sec. III-F describes the various types of simulated EME that may be of interest. The EME simulator may be an arbitrary signal generator or it may be composed of one or more actual emitters.

3) Interference Simulator: The interference simulator simulates the interference or appearance of the assigned (incumbent) device. Interference may be injected at various points in the network as shown in Fig. 1 using dashed lines. The interference signal is part of the EME and has the same properties as the general EME signal described in Sec. III-F. The chief difference is that the interference is intended to be the trigger for changes in the state of the PBR, while the rest of

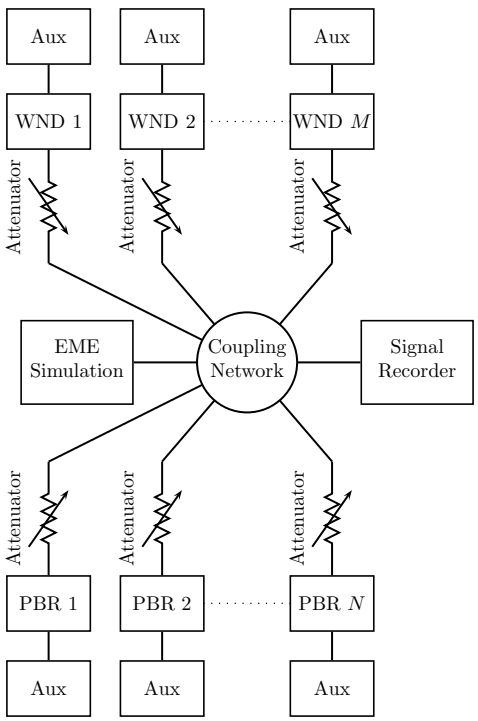

Fig. 2. Single DSA network test configuration with a network of legacy wireless network devices.

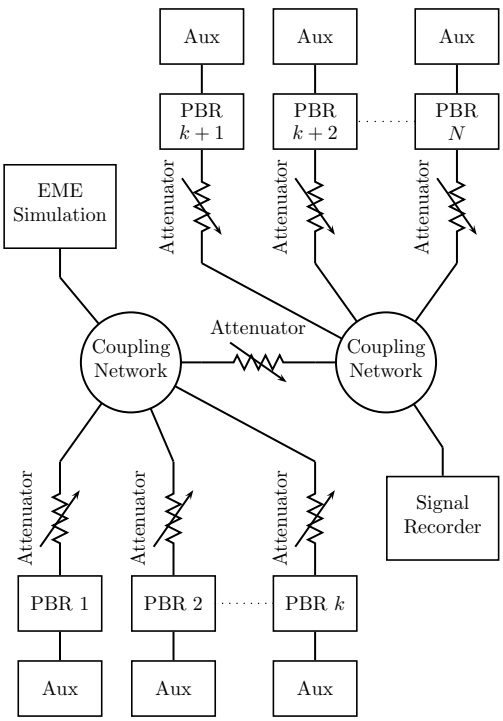

Fig. 3. Test configuration to simulate fragmentation or coalescence of a single N-node DSA network where the network fragments have size k and $N-k$. This arrangement can also simulate collision of two DSA networks.

EME provides the background environment where the changes occur. Of course, it is possible that the EME may cause PBR state changes subsequent to the initiation of the interference. In many cases, the same piece of test equipment can perform the EME simulation and the interference simulation.

An important test case concerns the use of a legacy system, such as legacy wireless network devices (WNDs), as the interference simulator. This allows the testing of the spectrum coexistence of DSA and non-DSA legacy system. Fig. 2 shows the test configuration for this situation.

4) Auxiliary Equipment (Aux): The auxiliary equipment provides the network loading and network measurement capabilities. It may also include computers, spectrum analyzers and other test equipment, microphones, video cameras, etc.

5) Coupling Network: The coupling network provides the RF connectivity for the PBR network. A functional coupling network may be achieved in various ways, and it is up to the user to determine the proper networking components. The network may consist of directional couplers, splitters/combiners, RF switches, and many other components. The user must ensure all components of the coupling network meet the frequency requirements of the DSA PBRs under test.

B. Multi-Network Setup

While the setup illustrated in Fig. 1 is useful for tests requiring a single DSA network, Fig. 3 illustrates the setup for two or more DSA networks required in such characterizations as network fragmentation, collision, and coalescence. In Fig. 3, an adjustable attenuator simulates variable path loss.

C. DSA Network Performance

The DSA network performance is characterized by abandonment time, initial network formation time, network join time, network migration time, initial network reconnect time, final network reconnect time, network fragmentation time, network collision time, network coalescence time, and the ability for network roaming. Our test framework allows for the characterization in an ideal lab environment, simulated real-world environment, and field test environment. Characterization parameters, such as frequency, bandwidth, frame length, modulation scheme, EME, power levels, etc., should be specified within the framework. Fig. 4 illustrates the relevant performance metrics when an interfering signal is introduced. The following describes these and other performance metrics.

1) Abandonment Time (T_a): Abandonment time characterizes the time required for the DSA network to abandon a channel after an assigned spectrum user, or an interference signal, start transmitting on said channel. This is a critical parameter since an assigned user must know the specific amount of interference a system will be receiving to decide whether to enable DSA in that spectrum. While the abandonment time is a system specification that is guaranteed by design, this performance parameter must be tested independently from the manufacturer.

2) Base Network Migration Time (T_b): Base network migration time characterizes the time it takes for the PBR master node to find an unoccupied frequency and start transmitting

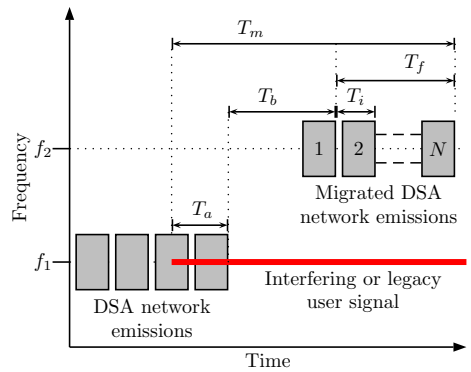

Fig. 4. Illustration of DSA network timing under interference condition.

on a newly selected operating frequency, after abandoning the previous channel.

3) Initial Network Reconnect Time (T_i): Initial network reconnect time characterizes the time required for the first slave node to reconnect to the master node after base network migration.

4) Final Network Reconnect Time (T_f): Final network reconnect time characterizes the time required for the last slave node to reconnect to the master node after base network migration.

5) Full Network Migration Time (T_m): Full network migration time characterizes the time it takes for the DSA network to abandon a channel, and have the master node and all connected slave nodes form a network and start communicating on a new channel. This is the sum of abandonment time, base network migration time, and final network reconnect time ($T_f = T_a + T_b + T_f$). The purpose of subdividing the full migration time into constituent time components is to obtain a better understanding of the scaling of the full migration time as a function of the number of nodes, EME, etc.

6) Initial Network Formation Time: Network formation time characterizes the time it takes one or more DSA-enabled PBRs to connect to the master node, form a network, and start transmitting data across the network. This parameter is to measure the formation of a new DSA network, after a fresh radio powerup, without any channel abandonment or network migration. The formation time may vary according to the RF network type (e.g. WiFi, WiMax, etc.) and network size.

7) Network Join Time: Network join time characterizes the time for one slave node to join a previously formed DSA network of two or more nodes. The time will vary depending on the parameters of the test (e.g. noise, interference, link attenuation, size of network, etc.). The slave node should not have prior information regarding the network's geolocation, cell size, or operating frequency.

8) Network Fragmentation Time: Network fragmentation time characterizes the time for one formed DSA network to fragment and form two smaller DSA networks. This is an important parameter as it predicts performance of DSA network in field situations. Allows for characterization of performance of the DSA network to validate the requirement of continuous, uninterrupted communications among users.

9) Network Collision: Network collision characterizes the performance of the DSA network when two separate co-located DSA networks operate on one frequency. Even though the use of DSA should prevent the two networks from colliding on the same frequency for an extended period of time, it is important to characterize the DSA network behavior to ensure uninterrupted communications among users.

10) Network Coalescence: Network coalescence characterizes the time required for two separate DSA networks approaching on the same frequency to coalesce into one single network. Even though adjacent networks generally should not coalesce on DSA-enabled PBR networks, network coalescence may be desired in certain tactical situations. It is especially important to characterize the DSA network behavior to ensure uninterrupted communications among users during unusual or unintended scenarios.

11) Network Roaming: Network roaming characterizes the ability of a slave node to roam among several DSA networks. This test is important to characterize the DSA network behavior in a mobile environment.

D. Policy-Based Control

PBRs require policies to enable use of DSA on communication networks. Policies dictate channels and/or behaviors which are allowed or disallowed by the system, depending on certain operational or environmental criteria. The goal of our test framework for policy performance characterization is to test the fidelity of the PBR with respect to executing the policy. We suggest the following parameters to be evaluated:

1) Dynamic Detector Threshold: The detector threshold specifies the levels, in dBm, at which the PBR can identify an assigned user or an interference signal causing the DSA network to abandon an operating channel. It is important to verify the capability of the PBR to dynamically adjust the detector threshold if it is too sensitive or not sensitive enough, depending on the operating RF environment of the DSA network. This characteristic is unique to systems employing energy sensing algorithms. Note the Dynamic Detector Threshold is a test of the capability of the DSA PBR only, not a test of a mode of operation. If dynamic thresholds are employed, a related system policy must also be in place to adjust transmitter parameters to ensure coexistence.

2) Power Control: Transmitter power is an important characteristic that determines if network communication will be successful. This test is used to characterize the effectiveness of a policy to dynamically control transmitter power levels of the PBR.

3) Selective Frequency Map: A selective frequency map specifies the operating range of the PBR, as well as specific frequency channels that are prohibited for use by DSA networks (as may be specified by a channel plan or other spectrum use regulations). This test characterizes the effectiveness of a policy to specify frequency bands on which the DSA network may and may not transmit.

4) Geospatial Operation: Geospatial operation requires the DSA network to be aware of its geospatial positioning. This awareness may be achieved through built-in or commercially available GPS simulators, which also allow for the simulation of moving or varying locations. Regulatory and system policies may be created that define geospatial operation within a certain distance of points, lines, or contours. This test characterizes the effectiveness of a policy to control the operation of the DSA network based on geospatial awareness.

5) Time-Based Performance: There are instances in which spectrum restrictions exist during certain days of the month, or certain times of day. This test characterizes the effectiveness of a policy to control the operation of the DSA network based on parameters of time.

6) Dense/Noisy Environment Performance: With an increased number of legacy systems being fielded, a decreased amount of spectrum available, and active military engagements all over the world, intentional and unintentional jamming is a major concern. This test characterizes the effectiveness of a policy to maintain communication while sustaining heavy interference or high-power jamming.

7) Threshold Sensing Accuracy: As described for the Dynamic Detector Threshold test in Sec III-D1, the threshold is a vital parameter that enables efficient use of DSA on the PBRs. This test characterizes the sensing accuracy of the detector to ensure the PBR is sensing the proper signal levels that are expected.

8) Composite Policy Performance: In a real field environment, a combination of any of the aforementioned policies may be running on the PBR at the same time. To ensure uninterrupted communications and operation of the PBRs as expected, this test characterizes the performance of the DSA network with multiple policies loaded and running simultaneously.

9) Cooperative Sensing: Characterizes the ability of multiple DSA-enabled PBRs to cooperatively detect and communicate the presence of a hidden node. This is an important characteristic to solve the hidden node problem in multi-node networks.

E. General Network Metrics

It is important to collect general network performance measurements to characterize the non-DSA specific metrics of the PBR network in a lab environment. Network metrics are network and application specific, and as such, cannot be exhaustively listed in the framework. The appropriate network metrics must be determined by the user, based on the specific application, type of DSA PBR, network routing protocol, and other parameters. The following items represent a small sampling of the network metrics to be performed as part of the DSA test:

- Payload Throughput
- Bit Error Rate
- Packet Error Rate
- Latency
- Jitter

F. Electromagnetic Environments (EME)

Radio frequencies are never used in an environment devoid of other electromagnetic activity. To simulate real-world conditions of RF environments and characterize their effect on the radio systems, electromagnetic signals need to be introduced with predefined characteristics. These include adjacent channel narrowband, wideband, wideband noise, frequency sweep, frequency hop, and high power signals. This portion of the framework allows for realistic testing in a lab environment, and allows for the creation of a baseline performance metric for a DSA-enabled PBR network. Comparison of baseline results with the EME-stressed results will provide a good indication of the performance of DSA in the field.

EME conditions are crucial to the operation of DSA PBR networks. Simulation of an EME for a testbed should be as realistic as possible to accurately measure the success of the DSA technology. Realistic EME may be achieved by survey, modeling and simulation of a real-world environment in the band of interest. Without such a process, real-world electromagnetic characteristics, including natural and man-made elements, may not be reproduced for testing against a realistic environment. The simulated realistic environment could serve as the electromagnetic ambient and other EME effects could be added to create different testing conditions.

1) Adjacent Channel Narrowband Signal: Adjacent channel narrowband signal is used to characterize the performance of the DSA network in the presence of an adjacent channel narrowband signal. The definition of narrowband depends on the frequency band of interest. For example, a common definition of narrowband signal in UHF/VHF range is occupied bandwidth ≤ 25 kHz.

2) Wideband Signal: Wideband signal is used to characterize the performance of the DSA network in the presence of a wideband signal. A wideband signal is defined as a signal having similar power and spectral density as the DSA radio signal.

3) Wideband Noise-Like Signal: Wideband noise-like signal is used to characterize the performance of the DSA network in the presence of a wideband noise signal. Based on our testing, we define wideband noise signal as signal with bandwidth greater than twenty times the occupied bandwidth of the DSA signal.

4) Frequency Swept Signal: Frequency swept signal is used to characterize the performance of the DSA network in the presence of a swept signal. A swept signal is a signal generated to sweep the operating band of the PBR. This may also affect the general networking measurements.

5) Frequency Hopping Signal: Frequency hopping signal is used to characterize the performance of the DSA network in the presence of a frequency hopping signal. A frequency hopping signal is generated to transmit in the operating frequency band of the PBR. The frequency hop rate should be set to characterize the radio in different simulated EM environments. This may also be performed in conjunction with the wideband or narrowband signals.

6) High Power Signal: This is used to characterize the performance of the DSA network in the presence of a high power signal. A high power signal is defined as a signal whose power is a pre-determined amount higher relative to the DSA-enabled PBR signal.

IV. Suggested Field Testing

A. Rationale

In this paper we are mostly concerned with the DSA test framework for laboratory testing. Laboratory testing is a practical and efficient method to thoroughly exercise all DSA features. The laboratory allows us to recreate a variety of EMEs, interfering signals and network configurations. Furthermore, laboratory testing facilitates measurements of various network and DSA metrics. However, a complete characterization of a DSA PBR requires an understanding of how the radio behaves under realistic field conditions.

B. Suggested Field Test Proposals

To gain a full understanding of DSA behavior in the field, the framework suggests repeating the tests provided in the DSA Network Performance and Policy-based Control sections of the framework, but without the ideally simulated or controlled conditions seen in the lab. The flexibility of the framework allows for the suggested field tests to be performed in conjunction with a combination of any of the characterizations and measurements previously described. By comparing characterization results from Test X performed under ideal conditions, Test X performed in the lab with specific EME signals introduced, Test X performed in the field under ideal conditions, and Text X performed in the field in an environment as suggested below, a complete understanding of the capability of the PBR and the DSA network can be obtained.

The suggested tests are not an exhaustive list of strictly required tests. These are only suggestions to enable a more complete characterization of DSA performance. It is up to the user to decide to perform field tests. However, the utilization of the proposed framework enables the user to characterize the behavior of any additional tests in a standardized format.

1) Urban Environment Performance Characterization: This characterizes the DSA network performance in an urban environment. The battlefield today is increasingly urban. By characterizing the DSA network performance in an urban environment, with building obstructions, indoors and outdoors communications, and very dense RF spectrum utilization (due to RF interference or assigned spectrum users, among others), a better understanding of DSA capabilities can be obtained.

2) Clear Line of Sight Performance Characterization: This characterizes the DSA network's line of sight performance on unobstructed, level terrain (or naval or aerial environment) where line of sight is always maintained. This may also be a good test to confirm the accuracy of the DSA network performance characterization done in the lab, with simulated distance between the DSA nodes by using attenuators, compared to the same test done in the field with physical distances separating the DSA nodes. This characterization will also help to establish anomalies associated with the DSA implementation

3) Unlevel Terrain Performance Characterization: This allows for characterization of the DSA network performance in various terrains, such as hilly, mountainous, valley, as well as various salinity and sea state conditions. The battlefield today is occurring on increasing varied terrain, with many hills, mountains, and valleys serving as great obstacles. The marine environment has also always posed a challenge due to the variety of ever-changing sea conditions present over substantial distances. By characterizing the DSA network performance while dealing with varied locations, terrains, and sea conditions, a realistic characterization of DSA performance will be obtained.

V. Conclusion

The proposed framework provides a baseline for characterization and testing of the emerging DSA technology. Key DSA-specific network metrics are identified and quantified for characterization of a network of DSA-enabled PBRs. A primary aspect of this framework is that it is extensible to a variety of network configurations. The framework provides methods of identifying the primary performance aspects of the DSA, devoid of the random effects that are encountered in a field environment. Furthermore the framework establishes extensions that enable field experimentation performance evaluations and clearly identifies component properties of the DSA susceptible to interactions with defined environmental elements. As DSA technology matures, and a varied number of DSA-enabled systems become available, the framework will evolve to incorporate comprehensive and standardized methods for performance comparisons and characterization.

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