AWS-3 Spectrum Sharing Assessment Process Improvement

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Abstract— ISART 2022 Call for Papers Topic Area: Retrospectives on AWS-3, CBRS, and AMBIT. **This paper provides an overview of how the AWS-3 Spectrum Sharing Test and Demonstration (SSTD) program used rigorous engineering analyses coupled with a Continuous Assessment Improvement Process (CAIP) to expand spectrum sharing in AWS-3 bands. During the AWS-3 pre-auction phase, basic models for assessing spectrum sharing were defined. The SSTD program was established as part of the DoD's AWS-3 Transition Plan to improve these models through rigorous test and demonstration to facilitate expedited and expanded entry of commercial deployments into the 1755-1780 MHz band. The paper describes the SSTD process for improving aggregate interference models through stakeholder collaboration using measurements, model prediction, and engineering rigor to reduce spectrum sharing model uncertainty, culminating in increased opportunities for successful deployment of commercial AWS-3 systems, while protecting DoD operations. An example comparing interference power measurements from an operational commercial network to aggregate interference model predictions over time shows how SSTD efforts have improved spectrum sharing in AWS-3 by reducing interference power predictions over 10 dB.**

Keywords—Advanced Wireless Services 3 (AWS-3), Spectrum Sharing, Long Term Evolution (LTE), Aggregate Interference, Propagation, Clutter Loss, Receiver Characterization, Modeling, Laboratory Testing, Field Testing, Measurements.

I. BACKGROUND

In July 2012, the Department of Commerce, National Telecommunications and Information Administration (NTIA), Commerce Spectrum Management Advisory Committee (CSMAC) convened working groups with membership from Federal agencies and commercial wireless operators to investigate the feasibility of sharing spectrum between commercial and federal systems. Working groups 2, 3, 4, and 5 considered the compatibility of federal systems in the 1755-1780 MHz band with commercial LTE User Equipment (UE). The working groups published their final reports in 2013 [2][3][4][5]. These reports provided much of the technical basis for the Federal Communications Commission (FCC) Report and Order (R&O) (FCC 14-31), dated 31 March 2014. This R&O established service, allocation, and technical rules for the AWS-3 bands: 1695-1710 MHz, 1755-1780 MHz, and 2155-2180 MHz. It also established requirements for commercial wireless broadband operators to coordinate with the Federal agencies when seeking to build out systems in the 1755-1780 MHz band.

On 29 January 2015 the FCC completed an auction of AWS-3 bands. The auction, designated Auction-97, raised (in net bids) a total of $41,329,673,325, with 31 winning bidders winning a total of 1,611 licenses. The auction exceeded expectations in terms of money raised and its completion initiated a 10-year transition period where most DoD systems operating in 1755-1780 MHz will cease or move operations to another band. Auction-97 winners that want to commence operations in pre-defined geographic Coordination Zones (CZs) must engage in the coordination process by submitting coordination requests (CRs) to DoD and other Government agencies to be granted early access, or early-entry to the spectrum licenses they purchased within defined CZ. Within DoD, DSO and each Military Service: 1) assesses whether the expected aggregate interference from a laydown specified in a CR will exceed the designated Interference Protection Criteria (IPC) for incumbent DoD receivers and 2) identifies which of the LTE sectors a CR are approved for early-entry.

II. ORGANIZATION OF THE PAPER/RELATED ISART 2022 PAPERS

This paper describes the approach and processes used on the SSTD Program to ***implement a circular, continuous assessment improvement process within the linear regulatory environment***. The paper is organized as follows: Sections III provide an overview of the SSTD program and describe the organizational process and the continuous assessment improvement process. Sections IV, V, VI, VII, and VIII describe the activities, findings, and recommendations of the work, focused on the four SSTD initiatives: Assess Aggregate Interference, LTE Characterization, Propagation Model Improvement, and DoD Receiver Characterization.

There are several other ISART 2022 papers related to the processes, findings, and lessons learned during the SSTD Program. These papers include:

- *SSTD Observations on Improved Spectrum Sharing* – describes SSTD observations and lessons learned.
- *SSTD Findings on AWS-3 Spectrum Sharing Assessments* – describes findings of AWS-3 spectrum sharing assessments.
- *Greenman: A Sector-based LTE Emission Model* – describes an SSTD-developed advanced LTE emission model.
- *Pathloss-Based Sector Uplink Emissions Model (PBSUEM) for LTE Aggregate Interference Prediction* – describes an uplink LTE emissions model for predicting aggregate interference.
- *Application of Gaussian Mixture Modeling Methods to Analysis and Prediction of Cellular Communications Pathloss Distributions* - describes machine learning techniques used for predicting LTE interference.
- *A Comparison of Data-driven Clutter Loss Clustering Models for New Site Interference Assessment* – describes a Machine Learning techniques for predicting clutter loss.

The SSTD recommendations under each Working Group initiative are summarized in this paper and are detailed in SSTD Findings on *AWS-3 Spectrum Sharing Assessments*.

III. SSTD Program Overview

The SSTD Program was established to 1) Facilitate Expedited and Expanded Entry (FEEE) of commercial deployments into the 1755-1780 MHz band, 2) Identify, Assess, Test/demonstrate, and Operationalize (IATO) coexistence assessments, interference mitigation, and other spectrum sharing enablers that support increased sharing between LTE and incumbent DoD systems, and 3) to support DoD's use of LTE technologies.

To achieve its objectives, the SSTD Program focuses on four broad technical areas for interference analysis improvements:

1) Assessment of the Aggregate Interference from early-entry LTE systems
2) Characterization of LTE systems and their emissions
3) Propagation Modeling between early-entry LTE systems and DoD receivers
4) Characterization of DoD Receiver performance in the presence of received LTE systems emissions

Multi-organizational technical teams were formed in each of these four areas, shown in Figure 1, to conduct research and analyses in support of an increasingly realistic assessment of spectrum sharing between DoD and AWS-3 LTE early-entry commercial deployments. In addition to their technical work, each team facilitates, engages, and collaborates with government communities of interest, in the form of working groups and "tiger teams". These groups bring together a wide range of stakeholders and subject matter experts from the DoD spectrum management community, Military Service research laboratories, and various other government and commercial support organizations.

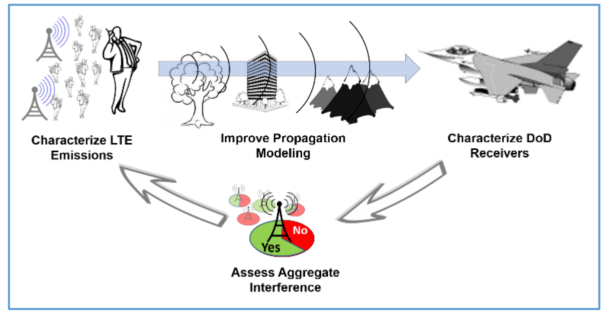

Fig. 1. AWS-3 Early-Entry Assessment

A. SSTD Continuous Assessment Improvement Process

At the onset of the SSTD program, only 7 months before the AWS-3 Early Entry portal was scheduled to come online, an initial approach to assessing AWS-3 licensees' requests for early entry had been established by government stakeholders. The approach, based on recommendations made by AWS-3 licensees during CSMAC 2012, recommendations published by the ITU, and the advice of government subject matter experts, was thought to be conservative. In keeping with the FCC rules (FCC-14-31A1 § 222), SSTD was tasked to facilitate commercial use of the band by working with stakeholders to increase realism in the models used to assess AWS-3 early entry requests.

> *"We expect a good faith effort from both the AWS-3 licensees and the Federal incumbents to share information about their systems, agree to appropriate interference methodologies, and communicate results so as to facilitate commercial use of the band"* [6]

In pursuit of improving AWS-3 early entry, SSTD established a Continuous Assessment Improvement Process (CAIP) depicted in Figure 2.

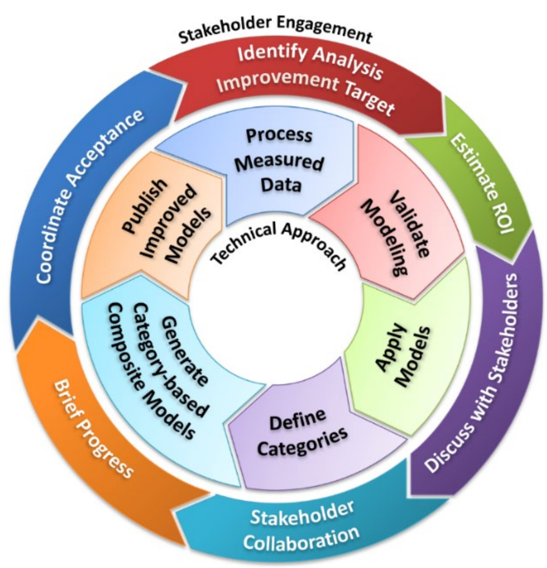

Fig. 2. SSTD Continuous Assessment Improvement Process (CAIP)

The CAIP incorporates two separate but related activity cycles. The outer ring captures the important elements of stakeholder engagement for each improvement. The inner ring captures the technical approach used to develop the improvements.

1) Stakeholder Engagement

Identify Analysis Improvement Target – The stakeholder engagement process starts by SSTD researchers collaborating to identify a set of possible AWS-3 analysis improvements. A series of meetings within the SSTD initiative performer groups and a program-wide meeting are used to identify possible improvements.

Estimate ROI – A Return on Investment assessment is performed on each identified analysis improvement target. Considerations for the level of research effort, impact on AWS-3 assessments, and implementation level of effort are all considered.

Discuss with Stakeholders – The stakeholder engagement continues by working with stakeholders to identify the set of improvements that will be considered during the next CAIP cycle. SSTD has implemented a cycle timeline of one year. At the beginning of each year, SSTD holds an SSTD Technical Synchronization Summit (STSS) where all researchers brief their best ideas for improvements and stakeholders provide feedback and help decide which improvements will be pursued.

Stakeholder Collaboration – For each targeted improvement, stakeholder points of contact and technical teams are identified. These collaboration groups can be informal, but they must at a minimum ensure that stakeholder management and technical teams are cognizant of all the research and have an opportunity to influence and direct the research.

Brief Progress – On a 4-week repeating cycle, each SSTD workgroup meets so that stakeholders can receive status updates. There are 3 workgroups: LTE Characterization, Propagation Improvement, and DoD Receiver Characterization/Aggregate Interference.

Coordinate Acceptance – At the end of the year, all research that yielded an actionable assessment improvement is summarized in the form of a formal recommendation and sent to stakeholders for concurrence. Once approved the recommendation is passed on to the business process technical teams to implement.

2) Technical Approach

Process Measured Data – At the onset of the cycle where researchers work on assessment improvements, efforts are made to acquire, and process measured data that can be used to inform those improvements. Everything from measurements on operational network interference levels, to clutter loss or building entry loss, to the geospatial extent of AWS-3 sectors, to coexistence testing between commercial and government systems is possible here.

Validate Modeling – Candidate models used for assessing AWS-3 early-entry undergo a validation process. Validation may come by comparing results to a known trusted model, such as the AT&T System Level Simulator used to predict LTE 4G/5G network performance, and/or by comparing model predictions to measured data. For example, if the current clutter loss models that help estimate the RF isolation of AWS-3 UEs from DoD receivers are targeted for improvement, measurement data that provides an indication of clutter loss is compared to the results of new or enhanced analytical techniques for predicting clutter loss. The best technique that does not over-predict the clutter losses observed from measurements, becomes the validated technique.

Apply Models – Once a set of techniques has been chosen, they are used to make predictions for a large number of operational scenarios, referred to as Site Assessments (SA). For example, a validated technique for clutter loss uses the Terrain-Integrated Rough-Earth Model (TIREM) and Light Detection and Ranging (LiDAR) data to make its predictions. LiDAR from various areas across the US is acquired and used to make clutter loss predictions called Clutter Site Assessments (CSA).

Define Categories – The AWS-3 business process for assessing early entry coordination requests must be able to easily estimate aggregate interference from any sector. Site-specific modeling, where each sector is assessed by a validated technique in the AWS-3 business process, is the goal but is often impractical due to the availability of required geospatial data (e.g., high resolution digital terrain and surface models) or computational tractability (e.g., 10,000 sectors assessed for 10 incumbent systems in 2-3 days). When site-specific assessments are not implementable in the AWS-3 business process, a site-general approach using categories is used. Here, a category model that leverages only data available to the business process is used to determine which category a site belongs too. Category models or definitions are determined by augmenting SAs with other feature data from the nationwide geospatial datasets that will be available to the business process. Augmented SAs are studied using various methods, including artificial intelligence/machine learning methods, to discover an optimal set of categories and a model for identifying membership.

Generate Category-based Composite Models – Once a category algorithm is chosen, researchers go back to the SAs and create a model for each category based on combining the SA results for each category member.

Publish Improved Models – Document the improvements in the form of a SSTD recommendation and provide them to stakeholders for approval.

B. SSTD Organizational Processes to Achieve Objecitves

The DSO is responsible for providing common DoD services including the overarching capabilities and analyses required to implement the DoD's Transition Plans for AWS-3. The DISA DSO Transition Plan includes six tasks, each supporting different DoD transition activities. The first of these tasks, referred to as DISA 1: 1755 – 1780 MHz Early Entry Portal, provides an efficient way to submit, assess, coordinate, and approve early entry LTE deployment requests from industry. The SSTD Program is the fifth transition plan task (DISA5) and provides technical enhancements to DISA1 evaluation capabilities and other analytical tools used to facilitate early entry during the transition period. DSO oversees all SSTD activities to ensure all work is fully coordinated amongst stakeholders/performers and is focused on the SSTD objectives. They accomplish this through monthly working groups (WGs), illustrated in Figure 3.

- LTE Characterization Working Group: Assess accurate predictions of LTE emissions and facilitate access to LTE information that can support DoD's use of LTE. The activities addressed in the LTE WG are broadly grouped into the following task areas:
  - Collect/analyze/assess LTE emissions measured data,
  - Develop/refine LTE sector categories and LTE emissions models and recommendations,
  - Identify/develop/assess LTE spectrum sharing techniques, and
  - Identify and provide information/support for DoD's use of LTE.

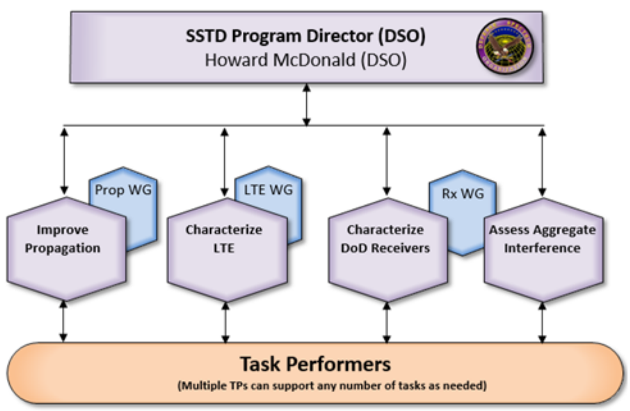

Fig. 3. SSTD Working Groups

- Propagation Model Improvement Working Group: Assess improvements to predicting RF propagation losses to support spectrum sharing - The activities addressed in the Prop WG are broadly grouped into the following task areas:
  - Collect/analyze/assess measured propagation data, and
  - Develop/validate/refine propagation and clutter categories/models.
- DoD Receiver and Aggregate Interference Working Group: Assess improvements to predicting LTE aggregate interference (AI) and its effects on DoD receiver performance degradation. The activities addressed in the Rx/AI WG are broadly grouped into the following task areas:
  - Collect/analyze/assess receiver data,
  - Coordinate and oversee carrier coordinated testing (CCT), and
  - Develop/refine LTE AI and receiver analyses models/recommendations.

The various SSTD performers coordinate and present their activities through these WGs as illustrated in 3. The DSO oversees all the SSTD WG meetings and activities. Each WG is co-chaired by one or more DSO support contractors and FFRDC/UARC staff. These WG meetings provide a forum for all SSTD stakeholders to review and discuss ongoing performer activities, and to recommend: 1) improvements to enhance the accuracy and realism of the analytical tools used to evaluate AWS-3 CRs, and 2) potential interference mitigation techniques that support increased sharing between LTE and incumbent DoD systems.

Figure 4 depicts two high-level contexts for AWS-3 sharing that are addressed by the SSTD program. Within each of the two broad contexts important scenarios are identified and assessed relative to FEEE and IATO.

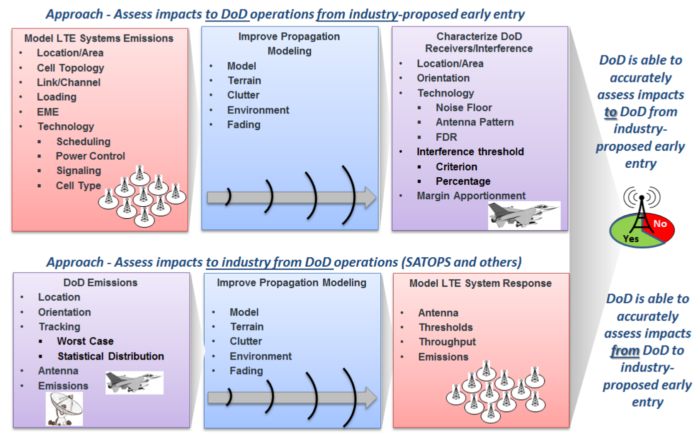

Fig. 4. SSTD Primary Contexts

IV. Assess Aggregate Interference

The DoD assessment of the impact to DoD operations from CRs begins with a comparison between the expected interference power from the LTE sectors in the carrier's CR, to each DoD system whose CZ includes those sectors. The total interference power that a DoD system can receive, without impact to operations, is defined by the system's Interference Protection Criteria (IPC). Because the CZ for a DoD system is likely to include many AWS-3 License Areas (LA) and to avoid a first come first served scenario for AWS-3 licensees, the total interference power limit, defined by the IPC is divvied up or apportioned, to the LAs in the CZ. Figure 5 shows an example of how a portion of the IPC-specified interference power threshold (for a DoD receiver at the center and a CZ in the circle) is allocated to the CRs (A – F) for the LA.

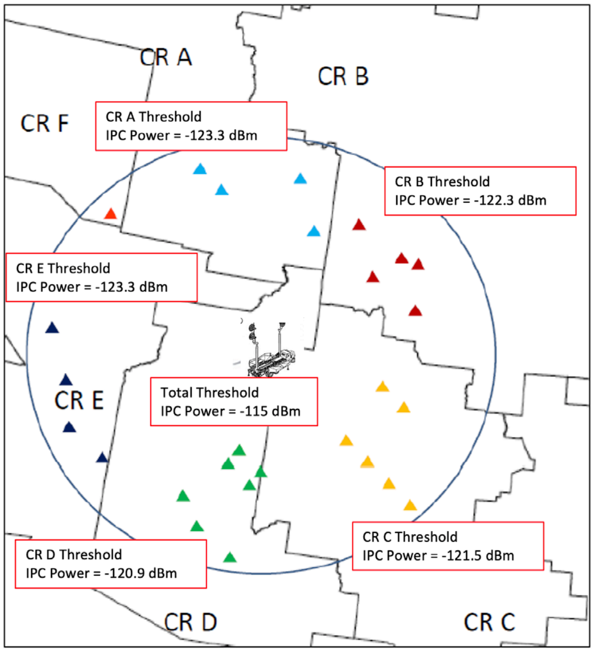

Fig. 5. Margin Apportionment Example

DoD currently uses a UE-based aggregate interference model to determine the expected interference power from the LTE base station laydown in a CR. The interference power from each modeled UE in the laydown is calculated according to (1).

$$I_k = NL(P_{Tx}) + EIRP(P_{Tx}) - L_{Cl}(P_{Tx}) - L_p(P_{Tx}, P_{Rx}) - FDR(\Delta f) + G_r(\theta, \phi) - L_{pol} - L_s \qquad (1)$$

Where:

I_k = predicted interfering signal level in the DoD receiver from a single modeled UE, dBm

$NL(P_{Tx})$ = Network Loading factor, dB (Factor to account for below full capacity LTE system traffic)

$EIRP(P_{Tx})$ = modeled UE transmitter Effective Isotropic Radiated Power, dBm

$L_{Cl}(P_{Tx})$ = Clutter Loss between a modeled UE and a DoD receiver, dB

$L_p(P_{Tx}, P_{Rx})$ = interference path Propagation Loss between a modeled UE and a DoD receiver, dB

$FDR(\Delta f)$ = Frequency Dependent Rejection, dB (Amount of UE power rejected by receiver selectivity)

$G_r(\theta, \phi)$ = DoD receiver antenna Gain in the direction of the interferer transmitter, dBi

L_{pol} = DoD receiver antenna Polarization mismatch Loss, dB

L_s = DoD incumbent receiver System Loss, dB

P_{Tx} = modeled UE transmitter location

P_{Rx} = DoD incumbent receiver location

Notes: θ and ϕ represent the elevation and azimuth angle between the Tx and the Rx. I_k, $EIRP(P_{Tx})$, and $L_{Cl}(P_{Tx})$ are modeled as random variables.

Equation (2) is used to determine the total interference power from a CR laydown to a DoD receiver which is modeled as a random variable. In addition to specifying an IPC, an associated confidence interval is also provided for each DoD system. This system's confidence interval is used to determine the LA confidence interval. If the expected interference level at the specified confidence interval, from an early-entry CR exceeds the interference power apportioned to the LA, sectors are removed in the CR are until the IPC for the LA is not exceeded.

$$i_{total} = \sum_{k=1}^{N} 10^{\frac{I_k}{10}} \qquad (2)$$

Where:

I_k = predicted interfering signal level in the DoD receiver from a single modeled UE, dBm

i_{total} = total interference power, mW

N = the number of modeled UEs

SSTD is engaged in a number of activities to assess and refine, not only the input parameters used in the model but also the model itself. A highlight of these activities is provided here.

A. Assess Aggregate Interference Activities

DoD Model Verification and Validation (V&V) – In an effort to improve DoD AWS-3 assessments, SSTD in coordination with LTE Carriers, is conducting in a series of field tests designed to verify and validate DoD aggregate interference models. In these tests, for a 48-hour period, SSTD measures LTE aggregate emissions while the coordinating LTE Carrier collects Key Performance Indicator (KPI) data from the AWS-1 LTE sectors in the area of the measurement location. Separately, SSTD conducts propagation measurements to determine site-specific clutter loss estimates. The measured data is then analyzed and compared to predicted model results for the test scenario. The first phase of the comparison is performed using default input parameters for Effective Isotropic Radiated Power (EIRP), Network Loading (NL), Clutter Loss, and UE location. In subsequent phases Carrier KPI, sector configuration data, and SSTD Clutter estimates are used in the aggregate interference models. Several V&V tests have been conducted and the results have been used to help validate model improvements.

Improve Margin Apportionment – As described above, in order to avoid a first come first served scenario for AWS-3 licensees, the total interference power limit defined by the IPC is divvied up, or apportioned, to all LAs in a CZ. In an effort to ensure that the DoD process will maximize AWS-3 early-entry, SSTD conducted a study to determine the optimal approach to apportioning margin to LAs in each CZ.

Improve Confidence Intervals – As described above, the confidence interval used with the interference power distribution for a DoD system is used to determine each LA's confidence interval. Simply using the aggregate confidence interval for each LA leads to a significantly higher total confidence interval. In an effort to ensure that the DoD process will maximize AWS-3 early-entry, SSTD conducted a study to determine the optimal approach to calculating the confidence interval to use for each LA in a CZ.

B. Assess Aggregate Interference Findings and Implications

Carrier Key Performance Indicators (KPI) Data Reliability – One aspect of the V&V testing described above includes SSTD LTE Field Measurement in some of the sectors monitored during the test. One of the purposes of this, is to determine if Carrier KPI data is reliable by directly comparing it to measurements. All test events conducted thus far have shown that Carrier KPI data is a reliable proxy for a direct measurement. One implication of this finding is that SSTD can leverage nation-wide Carrier KPI data to improve both site-general and site-specific LTE emission models.

Margin Apportionment – SSTD developed an approach to improve margin apportionment that leverages a proxy for a fully built-out LTE network. With the proxy laydown and detailed description of the calculation of aggregate interference, it is possible to determine in advance of the submittal of CRs, how much interference power to reserve, or apportion, to each LA to achieve the maximum possible approvals for early entry requests. The implication of this finding is that more sectors will be approved in early-entry requests.

LA Confidence Intervals – SSTD developed two approaches in pursuit of LA confidence intervals. One leverages a closed-form solution based on an assumption that aggregate interference is Gaussian. The other is an iterative method that assigns lower confidence intervals to each LA until the aggregate confidence interval is achieved. The implication of this finding is that lower confidence intervals can be used when evaluating CRs thereby allowing more sectors to be approved in early-entry requests.

C. Aggregate Interference Recommendations

	Aggregate Interference Recommendations
FY19 Confidence Intervals	Modify the per License Area CR Confidence Interval to a value derived from the LA with the most margin for a given Spectrum Access Record (SAR).
FY20 Confidence Intervals	Modify the per License Area CR Confidence Interval to a value derived from the LA that includes a safety factor.
FY21 Confidence Intervals	Modify the per License Area CR Confidence Interval to a value derived from the LA and a proxy laydown of LTE base stations in the area. It includes a safety factor that is optimized for each LA probe point pair.

V. LTE CHARACTERIZATION

As noted in the introduction, CSMAC 2012 considered the compatibility of federal systems in the 1755-1780 MHz band with commercial LTE UE. The compatibility assessment was based, in part, on industry recommendation for the modeling of LTE emissions documented in Appendix 3, Baseline LTE Uplink Characteristics of CSMAC 2012 WG 1 report [1], and has been determined to be an overestimate of LTE emissions. Many of the recommendations provided here were adopted by DoD at the onset of AWS-3 early-entry CR processing. SSTD is engaged in a number of activities to assess and refine not only the input parameters used in the model but also the model itself. A highlight of these activities is provided here.

A. LTE Characterization Activities

In pursuit of improved LTE emission models, SSTD has developed and is using a sophisticated LTE field measurement system along with fully automated lab measurement capabilities, including one with National Advanced Spectrum and Communications Test Network (NASTCN). As shown in Figure 6, field and lab measurements are cross-correlated with improved models to ensure the validity of model results.

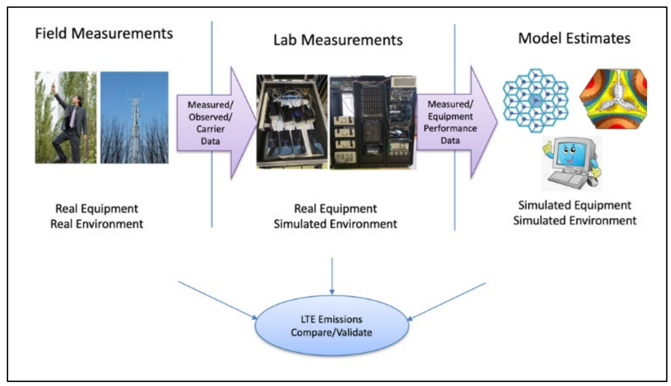

Fig. 6. LTE Emissions Characterization Field-Lab-Model Cross Validation Concept

LTE Field Measurement System - The SSTD program has developed and uses an LTE field measurement capability that includes Sanjole's Wavejudge/Intellijudge and LTE diagnostic UEs (TEMS). The system is used for many types of data collection including LTE sector surveys and capturing the millisecond by millisecond activity on both the downlink and uplink of operational LTE sectors. SSTD has collected data on over 70 sectors including traditional outdoor macro-cell installations in VA, MD, and CO, as well as indoor Distributed Antenna Systems (iDAS) sectors in buildings, a conference center, and a stadium.

LTE Lab Measurement Systems – SSTD developed and is using automated lab measurement systems with The MITRE Corporation and NASCTN, that use real LTE equipment in a simulated environment to explore the behaviors of LTE systems under a wide range of operating conditions. The nature of these lab-based measurements allows precise measurements of all LTE emissions under various equipment configurations and operating environments.

LTE Emission Model Development – SSTD developed and enhanced an LTE Emission Ensemble Model (LEEM) to predict UE emission distributions for a variety of LTE sector morphologies, operating configurations, and environments. In addition to modeling basic LTE control features, traffic models based on data collected from the SSTD LTE field measurement collections have been incorporated.

Advanced LTE Emission Models – Data captured from SSTD LTE field and lab measurements, as well as a better understanding of LTE operations, reveal that LTE emission models can be improved by migrating from UE-based to sector-based models. SSTD conducted research and development of a family of LTE sector-based emission models that are expected to simplify and better estimate LTE emissions.

Carrier Coordinated Modeling (CCM) – SSTD coordinated with AWS-3 Licensees to collect KPI and sector configuration data from a large sampling of operational LTE systems. This data was used to refine SSTD model inputs and produce more realistic predictions of LTE emissions.

Uplink Frequency Avoidance (UFA) – UFA is an interference mitigation technique that leverages capabilities of LTE networks to avoid allocating specific in-band uplink frequencies to UEs. SSTD program teams analyzed, evaluated and tested the technique to determine its operational efficacy; and coordinated with AWS-3 licensees and Service spectrum managers on technique implementation and impact on spectrum coordination analysis. UFA supports one of the primary SSTD objectives, IATO, by identifying an active interference mitigation technique that increases sharing between LTE and incumbent DoD systems.

B. *LTE Characterization Key Findings and Implications*

Impact of LTE Sector Size – Through collaboration with a major AWS-3 license holder and the use of several simulation models, SSTD showed that UE EIRP distributions are correlated to LTE sector size. This led to a recommendation to transition from the two current CSMAC "Rural" and "Urban/Suburban" UE EIRP curves, to a set of curves based on the estimated sector radius (related to sector Inter-Site Distance (ISD)) of the sectors being evaluated, plus a separate treatment for sectors defined as "small" that are covered by macro cells. The "family" of five macro cell curves and a separate non-co-channel small cell curve are illustrated in Figure 7 (The CSMAC distributions are included for reference). Co-channel small cells associated with approved macro cells are to be approved by rule per the accepted recommendation. (Note that the aggregate interference (AI) from the combined small and macro cells is LOWER than the AI from the macro cell alone.)

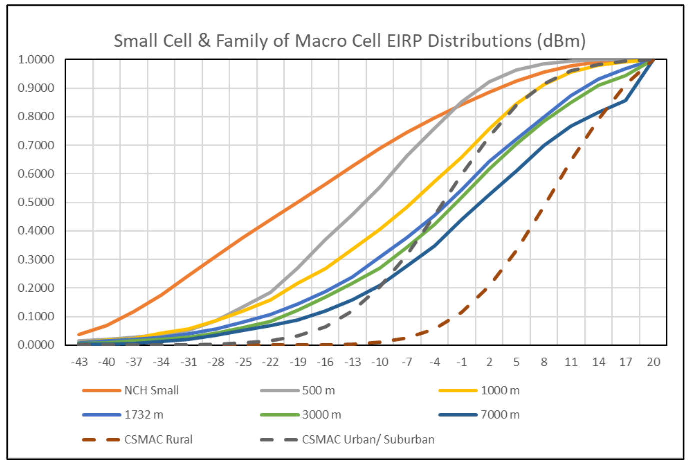

Fig. 7. Small Cell and Family of Macro Cell EIRP Distributions

Realistic LTE Network Loading – Using both a market penetration analysis of AWS-3 capable LTE UEs and a survey of LTE field measurements conducted on mature AWS-1 sectors, the SSTD team determined that LTE network loading is diurnal and peaks around noon local time. Peak (noon time) demand on average is 26% for Urban/Suburban and 16% for Rural, far lower than 100%. These NL values have been recommended and accepted by the stakeholder community.

Sector vs UE LTE Emission Models - Because of the complexities of sector propagation effects and the fact that LTE emissions are controlled and coordinated at the sector level to achieve a specified power per Physical Resource Block (PRB) PRB at the base station, the SSTD team has determined that it is more realistic to use sector-based LTE emission models that incorporate scheduling and other LTE power control features, rather than UE-based models.

Spectrum Sharing Using UFA – Using 3GPP specifications for in-band and out-of-band LTE emissions, SSTD developed a LTE emission mask for when UFA techniques such as PRB Blanking and Over Dimensioning were employed on early-entry LTE systems. This model showed that significant opportunities for spectrum sharing between LTE and narrow band DoD systems exist through the use of UFA techniques.

C. *LTE Characterization Recommendations*

	LTE Characterization Recommendations
Initial Operating Capability (IOC) LTE	• Use CSMAC 2012 Baseline LTE Uplink Characteristics of CSMAC 2012 WG 1 report • Use Census Bureau Urban shapefile to determine LTE emission category of Urban or Rural • Per agreement with Industry during an early Aeronautical Mobile Telemetry (AMT) WG, use Network Load values of 60% for Urban and 40% for Rural Note: SSTD did not have time to assess this proposal prior to IOC.

<table>
<tr><td>Network Loading - ACTS Tiger Team 2017</td><td>• Urban or Rural as determined by the Census Bureau Urban shape file
• Urban-Suburban/Rural NL = 30%/20%.</td></tr>
<tr><td>LTE Emission Mask - ACTS Tiger Team 2017</td><td>Model LTE guard bands in UE emission mask</td></tr>
<tr><td>LTE Uplink Frequency Avoidance - ACTS Tiger Team 2017</td><td>When carrier implements UFA; calculate “notched” PRB UE emissions from 3GPP IBE specification.</td></tr>
<tr><td>Network Loading FY19</td><td>• Urban-Suburban or Rural as determined by the Census Bureau Urban shape file
• Urban-Suburban/Rural # of simultaneous UEs of 3/5MHz of LTE Uplink BW (per CSMAC) with Urban-Suburban/Rural NL = 26%/16%, or
• Use Urban-Suburban/Rural # of simultaneous UEs of 2/5MHz of LTE Uplink BW with Urban-Suburban/Rural NL = 39%/24%</td></tr>
<tr><td>Small Cell FY20</td><td>• Aggregate interference (AI) from the combined small and macro cells is LOWER than the AI from the macro cell alone.)
• Use the AT&T non-cochannel one small cell EIRP curve associated with 1732m ISD macro cell for “standalone” small cells. (Note that this curve mean EIRP is 2.38 dBm and is 3.2 dB less (Equivalent EIRP) than the CSMAC suburban/urban curve.)</td></tr>
<tr><td>Network Loading FY20</td><td>Verifies and validates the FY20 Network Loading recommendation based on Carrier Coordinated Testing and Multi-Market data analysis. The FY19 Network Loading recommendation does not change.</td></tr>
<tr><td>Family of Macro Cells FY21</td><td>• Use the nearest neighbor distance algorithm to determine sector radius.
• Use the sector radius to ISD category map to select from 5 ISD-based UE EIRP categories.
<table>
<tr><th>Sector Radius (m)</th><th>ISD Category</th><th>FY21 Mean EIRP (dBm)</th></tr>
<tr><td><=375</td><td>500 m</td><td>-2.23</td></tr>
<tr><td>(375, 683]</td><td>1000 m</td><td>4.12</td></tr>
<tr><td>(683, 1183]</td><td>1732 m</td><td>8.20</td></tr>
<tr><td>(1183, 2500]</td><td>3000 m</td><td>9.25</td></tr>
<tr><td>>2500</td><td>7000 m</td><td>12.01</td></tr>
</table></td></tr>
<tr><td>Greenman Advanced Emission Model FY21</td><td>• Use sector antenna, system losses, and laydown information to calculate the RF Centroid for each sector.
• Use sector P0 and the FY19 NL recommendation for PRB occupancy along with the RF Centroid to assess sector uplink power.</td></tr>
<tr><td>Pathloss-Based Advanced Emission Model FY21</td><td>Pathloss-Based Sector Uplink Emissions Model (PBSUEM) for LTE Aggregate Interference Prediction</td></tr>
</table>

VI. Propagation Model Improvement

Propagation effects, including those due to terrain, atmosphere, and clutter (man-made structures and foliage) must all be considered when assessing the signal level of LTE emissions that reach DoD systems. Amongst these three types of propagation, clutter is perhaps the most complex and by extension the most difficult to assess. Because of the very long slant ranges associated with AWS-3 early-entry analyses (sometimes over 300 km), the effects of clutter are usually significantly lesser. This combined with DoD’s well-established expertise with terrain and atmospheric propagation modeling, led to the current approach which is to use terrain and atmospheric propagation models directly, as if there was no clutter, and then “add-in” the effects due to clutter. This is referred to as end-point clutter modeling. SSTD efforts to refine propagation modeling include an assessment of integrated propagation modeling, where terrain, atmosphere, clutter are all part of a single integrated model. SSTD engaged in a number of activities to assess and refine terrain, atmospheric, and clutter models as well as the category definition when the various models and/or distributions should be used. A highlight of these activities is provided here.

A. *Propagation Model Improvement Activities*

Propagation Field Measurements – SSTD has been working with propagation measurement teams, including NTIA’s Institute for Telecommunication Sciences (ITS) to, conduct high quality measurements that can support estimates of propagation including those due to clutter. Because of the difficulty associated with isolating the effects of clutter in a propagation path, care is taken to collect a significant number of propagation measurements on paths with no significant terrain or atmospheric effects so that the measurement minus the free space path loss can serve as a substitute for a direct measurement of clutter. SSTD has used both a ground-based and an airborne propagation measurement system to collect over 1 million discrete measurements throughout the US in all clutter morphologies and for elevation angles up to 50 degrees.

PMDNA – The Propagation Measured Data Normalization and Augmentation (PMDNA) effort in SSTD implements a process whereby all propagation measured data is normalized into a single data set with a standard set of well-defined fields. In addition to the normalization, the data set contains augmented fields that can hold any data including for example a simple elevation angle for each path or the result of various clutter model predictions for the path.

Clutter Model Development and Validation – SSTD clutter modeling activities focus on site-general models that use distributions of clutter loss or an equivalent scalar value for a set of clutter categories. Discovery of the number of categories, a process for category determination, and the best clutter modeling techniques for each category present a circular process for refinement. A significant part of the clutter model determination relies on the availability of measured data for a candidate category so that the clutter modeling technique can be validated against it. Once validated for a category, a model may be used any place that the category exists, to develop a larger sample from which to derive the category's clutter loss distribution. In the absence of a validated model for a given category, a statistically significant number of measurements, screened for measurement bias, can be used to populate the clutter distribution.

Propagation Model Development – Similar to clutter model development, propagation model development is focused on the set of categories and the model to use for each. Activities here involve the development of a trade-offs between different models based on their specific strengths. Included in the trade-offs is the scenario coverage and the computational time required.

B. *Propagation Model Improvement Findings and Implications*

Measurement Uncertainty - Due in part, to the high variability associated with propagation effects, even the highest quality propagation measurements can be +/- 7 dB from the same high-quality measurement taken at a different time. The primary implication from this fact is that a high number of independent measurements are needed to achieve statistical significance. A propagation model's estimate for a given path will never change unless the input parameters change, though it may give values for several confidence intervals.

Clutter Isn't Always a Loss – As illustrated in Figure 8, it can happen that a given path's clutter environment to create a signal enhancement due to multipath. Additionally, instances of clutter creating an enhancement in a field of emitters will have a big impact on estimates of aggregate interference. The implication of these two facts taken together is that it is important to ensure that a given model/distribution does not overestimate or underestimate the occurrence of a clutter-based enhancements. Further, it is important to note that propagation measurements taken over short ranges will be affected more by the presence of multi-path than measurement taken over longer ranges. The implication here is if using short range measurements to estimate the effects of clutter over longer paths an increase in clutter loss estimates is required.

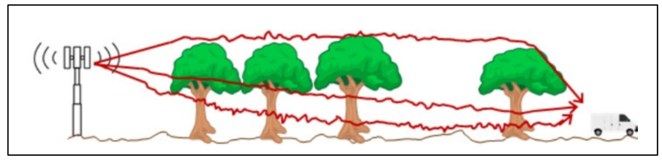

Fig. 8. Propagation Enhancement from Clutter

Equivalent Clutter Loss – Propagation distributions/statistic are often given in dB units and while statistics on dB distribution are useful in communicating the shape of a distribution in dB, they can be quite misleading when assessing the relative impact of using one distribution vs another in an aggregate interference assessment. To avoid the issues associated with this, SSTD has developed equivalent clutter statistics that allow for a direct comparison amongst many distributions that are indicative of the impact that one distribution or another will have in an aggregate interference assessment.

Elevation Angle Matters – Both SSTD measurements and clutter model techniques show that the higher the elevation angle between the UE and the DoD receiver, the less the expected clutter loss. The implication for this is that it's important to use elevation angle as a clutter category selector to ensure that results are not over or under predicting the effects of clutter.

Morphology Matters – It is well established that the morphology associated with given propagation path will have an impact on the effects due to clutter. The implication for this is that it's important to use morphology as a clutter category selector to ensure that results are not over or under predicting the effects of clutter.

Clutter Models vs Clutter Measurements - Because of the difficulty and expense of making high-quality propagation measurements, an effort to fully characterize the clutter loss expected from UEs located throughout a sector, to one or more receiver positions would be substantial. Measurement drive testing is an approach that is often used but only captures clutter loss values for a small portion of UE locations in the sector (i.e., those UEs on the street). Because of this, a clutter loss model that used only drive test measurement as a guide would suffer from measurement bias. Clutter loss modeling happens in a computer and can be assessed for any area where the required input parameters (e.g., clutter height data) are available. Because of this, clutter loss models derived from measurement-validated techniques will produce a more comprehensive result that will avoid measurement bias.

Machine Learning-Based Enhanced Clutter Model – Recently SSTD has conducted research and development of Machine Learning algorithms for predicting clutter loss. Two approaches have been pursued: clutter loss category models and clutter loss distribution prediction models. Both approaches appear to be successful. The distribution prediction models predict the actual clutter loss distribution from a set of morphological and topographical inputs. Details on the approach and results of machine learning-based clutter modeling effort are described in the ISART 2022 paper: *A Comparison of Data-*

driven Clutter Loss Clustering Models for New Site Interference Assessment.

C. Terrain/Atmospheric Propagation Effects

The Federal Aviation Administration's (FAA's) new aircraft collision and avoidance system infrastructure, Mode-S. Mode-S is a communication system set in place by FAA to serve as a next generation-self-reported radar system; mandated on all commercial aircraft. Through the Mode-S Automatic Distributed Surveillance-Broadcast (ADS-B) protocol, an aircraft provides its: identification number, position, altitude, velocity, bearing, and other information as an unencrypted broadcasted message. FAA operates a large set of ADS-B CONUS receivers that record the messages along with the received power associated with each one. This information makes it possible to deduce the path loss between the aircraft and any ground station (up to 40) that was able to detect each ADS-B transmission. SSTD performers have acquired ADS-B message data with received power collected by the FAA in 2019 and 2020, which has ~10.2 TB of HDF-5 files (compressed), ~140,000 unique aircraft, and ~50 million flight hours.

D. Clutter Loss Measurement Techniques

A key part of the clutter model development process involves conducting clutter measurement campaigns to empirically characterize clutter loss in various morphologies and for different geometries. Two direct clutter measurement techniques that use "existing signals" are being developed under the SSTD program. These techniques leverage the ubiquitous nature of Global Positioning System (GPS) and Automatic Dependent Surveillance-Broadcast (ADS-B) signals to directly measure clutter. Because both of these signals surround any location, they can be used to paint a propagation loss picture of the entire perimeter of an area. Both techniques are also thought to be suitable for making building enclosure loss measurements.

<u>GPS-Based Clutter Loss Measurement (GPS-BLCM)</u> – SSTD performers are developing a prototype system that measures GPS signals. This method accomplishes these measurements by utilizing GPS receivers to collect GPS Satellite signals across multiple clutter environments. The GPS Clutter Measurement System required to employ this collection methodology incorporates the use of two precision GPS receivers. One receiver is located within clear Line of Sight (LOS) to all GPS satellites within its field of view at a selected measurement location (the Reference Receiver), and the other (the Rover Receiver) is placed within a defined clutter environment within the Reference Receiver's geographic region. By comparing received signal levels at various azimuths and elevations from multiple GPS satellites simultaneously, as they pass, numerous clutter measurements are collected across multiple directions within the given clutter environment.

<u>ADS-B Clutter Loss Measurement</u> – SSTD performers are developing a prototype system that measures ADS-B data signals. This method accomplishes these measurements by utilizing ADS-B receivers to collect ADS-B signals from aircraft flying across the US across multiple clutter environments. The ADS-B Clutter Measurement System required to employ this collection methodology incorporates the use of two ADS-B receivers. One receiver is located within clear Line of Sight (LOS) to aircraft within its field of view at a selected measurement location (the Reference Receiver), and the other (the Rover Receiver) is placed within a defined clutter environment within the Reference Receiver's geographic region. By comparing received signal levels at various passing aircraft azimuths and elevations, numerous clutter measurements are collected across multiple directions within the given clutter environment.

E. Propagation Model Improvement Recommendations

	Propagation Model Improvement Recommendations
IOC Terrain & Atmospheric Path Loss	• Use P.528 for DoD Receivers above 5,000 ft • Use TIREM with 90m DoD Digital Terrain Elevation Data (DTED) data for DoD Receivers below 5,000 ft
IOC Clutter	• Segment between 4 clutter categories comprising of; 2 morphologies Urban or Rural as determined by the Census Bureau Urban shape file; and two DoD Rx height bins, above or below 5,000 ft • Models as a uniformly (in dB) distributed Random Variable (RV) with given Equivalent Clutter Loss (ECL) values • Urban G-G = 16.05 dB • Urban G-A = 1.32 dB • Rural G-G = 4.08 dB • Rural G-A = 0 dB
Early 2017 Clutter	• Use the SY morphology selection algorithm base on the National Land Cover Database (NLCD) for a given location • Differentiate by elevation angle • Models as RV with given ECL values

ECL Category	**G**	**3°**	**5°**	**7°**	**10°**	**20°**	**30°**	**50°**
DU	6.64	4.24	2.41	1.08	-0.38	-2.73	-2.06	-2.91
U	13.05	5.54	3.31	2.25	1.47	0.54	0.25	0.06
S	7.38	3.07	1.97	1.40	0.95	0.36	0.16	0.04
SF	14.32	9.71	6.57	4.81	3.32	1.44	0.80	0.28
R	13.94	1.95	0.07	0.01	0	0	0	0
RF	18.96	18.28	16.97	15.14	12.63	4.3	0.16	0
B	0	0	0	0	0	0	0	0
Note: U=Urban, D=Dense, S=Suburban, R=Rural, F=Flat, Fo=Forested, B=Barren								

ACTS TT Mid 2017 Clutter	• Map the results for SSTD Early 2017 Clutter back to the 2 IOC G-A categories using a uniform distributed (in dB) random variable • Urban G-A = 2.83 dB • Rural G-A = 1.56 dB

ACTS TT Mid 2017 Terrain Interaction	• For DoD Rx heights above 5,000 ft and when a terrain interaction is present, use TIREM to calculate path loss analysis; otherwise use P.528
FY19 Clutter Framework	• Model Clutter as a random variable with a matrix of MxN distributions where M in the number of morphologies and N is the number of elevation angle bins
FY19 Terrain and Atmospheric Models	• Use IF-77 for DoD Receivers above 5,000 ft • Use TIREM with 90m DoD DTED data for DoD Receivers below 5,000 ft
FY19 Clutter Distributions	• Use the CASY morphology selection algorithm base on the NLCD for a given location • Differentiate by elevation angle • Model as RV with given ECL values

ECL	1.5°	3°	5°	7°	10°	20°	30°	50°	70°
DU	11.88	8.24	4.35	4.31	3.41	1.72	0.58	-0.88	0.99
U	12.00	7.89	5.49	4.14	2.94	1.29	0.68	0.20	0.02
S	8.63	5.58	3.79	2.80	1.93	0.80	0.41	0.12	0.01
SF	9.10	7.03	5.70	4.76	3.74	2.04	1.33	0.61	0.19
R	1.99	1.27	0.83	0.60	0.42	0.19	0.11	0.04	0.01
RF	9.79	7.58	5.96	4.99	4.02	2.39	1.64	0.85	0.32
B	0	0	0	0	0	0	0	0	0

Terrain Database	• Upgrade the terrain database used in the AWS-3 business process from DoD DTED Level 1 data to USGS DEM Level 2 data
FY21 Clutter Distributions	• Use the CASY morphology selection algorithm base on the NLCD for a given location • Differentiate by elevation angle • Model as RV with given ECL values • Use the 5m Intermap DTM and DSM to calculate average clutter height to choose Flat category for each morphology

ECL	1.5°	3°	5°	7°	10°	20°	30°	50°	70°
DU	9.51	6.93	5.81	4.72	3.57	2.56	1.83	1.56	2.47
DUF	13.53	11.41	9.47	8.25	6.85	5.09	3.93	3.11	3.74
U	9.85	7.39	5.35	4.12	3.01	1.43	0.79	0.24	0.02
UF	11.84	8.93	6.58	5.19	3.93	2.05	1.27	0.51	0.11
S	3.95	2.89	2.13	1.70	1.31	0.70	0.43	0.14	0.02
SF	10.16	7.59	5.68	4.52	3.42	1.78	1.09	0.44	0.11
SFo	9.58	7.89	6.31	5.26	4.21	2.55	1.76	0.84	0.22
SFoF	13.99	11.18	8.99	7.52	6.03	3.57	2.45	1.23	0.40
R	0.45	0.34	0.29	0.26	0.24	0.21	0.14	0.03	0.00
RF	3.06	2.07	1.49	1.21	0.95	0.60	0.44	0.19	0.04
RFo	3.27	2.86	2.51	2.32	2.11	1.72	1.41	0.77	0.24
RFoF	9.66	7.48	5.93	4.98	4.09	2.66	1.99	1.16	0.43
B	0	0	0	0	0	0	0	0	0

VII. DoD Receiver Characterization

When considering the impact to a DoD system/receiver when operating in the presence of aggregate interference from a field of UEs, both electrical characteristics and the operational parameters for the equipment must be considered. DoD system IPCs and receiver selectivity curves are used to address the electrical characteristics. Operational parameters look at where the system operates. SSTD conducts research into both areas, in an effort to achieve increasingly realistic estimates of DoD system performance when sharing spectrum with commercial LTE systems. A highlight of these activities is provided.

A. DoD Receiver Characterization Activities

<u>Equipment Measurements</u> – SSTD supports Service testing efforts designed to identify the IPCs required to ensure that DoD operations will not be impacted when sharing spectrum with LTE systems. Multiple DoD systems that operate in the AWS-3 band have been tested.

<u>DoD Receiver Position Modeling</u> – Many factors go into establishing and maintaining areas in the US where DoD equipment can safely operate. SSTD is engaged in efforts to understand the difference amongst the areas where AWS-3 DoD systems operate and how those systems are used in those operational areas. This is an important part of establishing not only the proximity of DoD systems to LTE systems, but also the range of desired signal levels that may be experienced.

<u>Assess IPCs</u> – SSTD worked with the Services to collect data on equipment measurements and operational areas to identify improvements in DoD system IPCs.

B. DoD Receiver Characterization Findings Implications

<u>Signal to Interference plus Noise Ratio (SINR)-based IPC</u> - At the onset of AWS-3 CR processing, Interference to Noise Ratio (INR)-based IPCs along with receiver selectivity curves were used to assess the impact of received interference power on DoD system performance at the location of the receiver. This approach requires that you only assess the interference power into the receiver and compare it to the documented noise floor for the system. While straightforward, this approach does not consider the strength of the DoD system's desired signal and by extension the SINR, which is a much better estimate of system performance. The implication of this finding is that DoD systems that do not operate at the edge of their design limits can accept higher interference power without impact on system performance which allows more sectors to be approved in an early-entry CR.

<u>SINR-based IPCs for INR-based Models</u> – The current DoD model for assessing LTE early-entry requests is based solely on INR. SSTD has developed a mathematical approach, to convert a SINR value into an equivalent INR. The implication of this

finding are that when knowledge of the desired signal is available, DoD can use this information in an INR-based model and allow greater access for early-entry CRs.

DoD System IPCs – For a number of DoD systems the operational areas suggest that the equipment does not need to operate at its design limits and as such has a higher minimum SINR. This in turn means that the IPC for these systems can be raised with the implication that more access to early-entry LTE systems can be granted.

C. Receiver Characterization Recommendations

	Receiver Characterization Recommendations
ACTS TT Mid 2017 ACTS Rx Antenna Height	Adjust altitude of ACTS airborne receivers to be consistent with range limits stated in Annual DoD Report to Congress on Inventory of DoD Ranges Worldwide. For SARS with multiple ranges/max altitudes use correct altitude for a given analysis location.
ACTS TT Mid 2017 ACTS refined Op Areas	Certain ACTS operating areas have been refined. A -6 dB I/N margin allocation for license areas outside of ACTS analysis zones to be used, will free up margin to be distributed to licenses inside the analysis zones. ACTS analysis zones are based on current ACTS Op Areas plus a stand-off distance
ACTS TT IPC Value	Assess the desired signal when calculating the tolerable interference levels
FY19 SINR->INR Mapping	For SARS with sufficient SINR revise the INR values used in the CR business process to provide an equivalent analysis
FY20 Polarization Loss	Account for 3dB of polarization loss when modeling DoD antennas remaining in the AWS-3 band at the end of FY20

VIII. SSTD Interference Modeling Expands Use of AWS-3 Band While Protecting DoD Assets

The results of the SSTD progressive aggregate interference analysis improvement have resulted in expanded entry of commercial AWS-3 deployments. Many technical advances have led to significant improvements in:

- LTE Characterization
- Propagation Modeling
- DoD Receiver Characterization
- Aggregate Interference Assessment

The results of CAIP in overall aggregate interference prediction, based on the combined SSTD recommendations is illustrated in Figure 9.

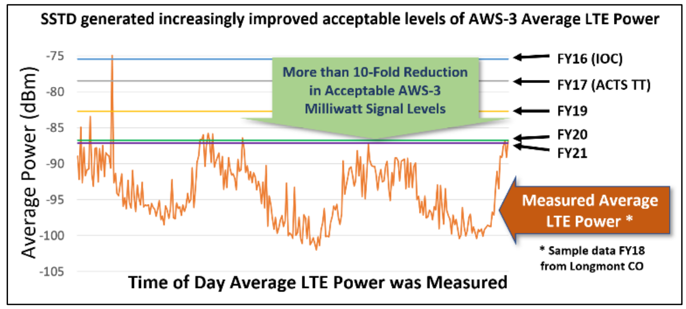

Fig. 9. SSTD Improvements in Predictions of Aggregate Interference

Additionally, in the execution of measurement and data gathering activities, the SSTD program has collected substantial reference data, some of which can be made available to other researchers. The types of data used include:

- Aggregate interference measured data from carrier-coordinated testing,
- "Multi-market (restricted)" LTE Radio Access Network cell parameters and key performance indicators (KPIs),
  - 9 days of 1-hour KPI data from all cells/sectors in 8 markets of varying sizes
  - >12,000 sectors from a major mobile network operator
- LTE Field measurement data,
- Propagation/clutter measurement data.

Details on the SSTD WG recommendations and the data that has been collected are available in ISART 2022 paper *SSTD Findings on AWS-3 Spectrum Sharing Assessments*.

IX. Conclusions

This paper described the approach and processes used in the SSTD Program to ***implement a circular, Continuous Analysis Improvement Process (CAIP) within the linear regulatory environment***. It also described the SSTD process for improving aggregate interference models through stakeholder collaboration using measurements, model prediction, and engineering rigor to reduce spectrum sharing model uncertainty, culminating in increased opportunities for successful deployment of commercial AWS-3 systems, while protecting DoD operations.

The paper summarized the activities and results of the four major initiatives that are part of the SSTD program: Assess Aggregate Interference, LTE Characterization, Propagation Modeling, and Receiver Characterization. Findings from each of these initiatives support the ability for DoD to conduct increasingly realistic modeling of the impacts from AWS-3 LTE early-entry systems to incumbent DoD operations in the band. An example comparing interference power measurements from an operational commercial network to aggregate interference model predictions over time, showed how SSTD efforts have improved spectrum sharing in AWS-3 by reducing interference power predictions by over 10 dB.

SSTD findings are focused on AWS-3 spectrum sharing but are also applicable to other spectrum sharing scenarios – particularly spectrum sharing between LTE/5G Frequency

Division Duplex (FDD) networks and DoD operations, and the techniques and many of the results can also be applied to spectrum sharing between LTE/5G Time Division Duplex (TDD) networks and DoD operations

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- **Air Force Spectrum Management Office:** Arsenio Ibay
  - HII (Alion): Bob Martin, Eric Germann, Jason Green, et al.
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