SSTD Findings on AWS-3 Spectrum Sharing Assessments

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***Abstract*— ISART 2022 Call for Papers Topic Area: Model Standardization. This paper provides an overview of the Advanced Wireless Services 3 (AWS-3) Spectrum Sharing Test and Demonstration (SSTD) program's most current findings relative to AWS-3 spectrum sharing assessments. Analytical model descriptions that are used for AWS-3 commercial wireless emissions; terrain, atmospheric, and clutter propagation loss; and Department of Defense (DoD) victim receiver characterization are described along with interference power aggregation and partitioning models. In addition, SSTD measurements and data sets are also described.**

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. INTRODUCTION

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, which was 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 all 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 CZs. Commercial deployments outside of the CZs are available immediately and are not required to go through the CR process. Within DoD, Defense Spectrum Organization (DSO) and each Military Service assesses: 1) whether the expected aggregate interference (AI) 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 in a CR are approved for early-entry.

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.

In order to achieve its objectives, the SSTD Program focuses on four broad technical areas for improvements, referred to as initiatives, focused on AWS-3 spectrum sharing. These are:

1) Characterization of LTE systems and their emissions,

2) Propagation Modeling between early-entry LTE systems and DoD receivers,

3) Characterization of DoD Receiver performance in the presence of LTE systems emissions, and

4) Assessment of the Aggregate Interference from early-entry LTE systems.

Multi-organizational technical teams have been formed in each of these four initiatives 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. Figure 1 illustrates the technical focus of each of these teams. In addition to their technical work, each team facilitates, engages, and collaborates with government communities of interest as well as AWS-3 licensees.

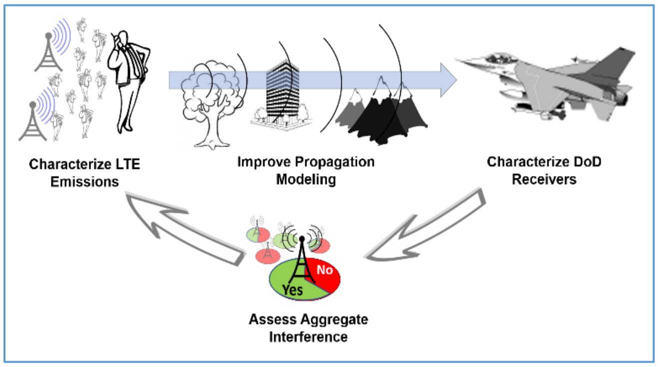


Fig. 1. AWS-3 Early-Entry Assessment

II. ORGANIZATION OF THE PAPER/RELATED ISART 2022 PAPERS

This paper provides the most current findings relative to AWS-3 spectrum sharing assessments. It is organized as follows. Sections III, IV, V, and VI each describe the current SSTD findings relative to AWS-3 spectrum sharing analyses. Each section is focused on one of the four initiatives: Characterize LTE Emissions, Improve Propagation Modeling, Characterize DoD Receivers, and Assess Aggregate Interference. Section VII provides an overview of SSTD measurements and data sets.

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

- AWS-3 Spectrum Sharing Assessment Process Improvement – describes the approach and processes used on the SSTD Program.
- SSTD Observations on Improved Spectrum Sharing – describes SSTD observations and lessons learned.
- Greenman Sector-based LTE Emission Model – describes a new advanced LTE emission model developed under the SSTD Program.
- 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 machine learning techniques used for predicting clutter loss.

III. CHARACTERIZE LTE EMISSIONS FINDINGS

During CSMAC 2012 the AT&T System Level Simulator (SLS) team provided a description of baseline LTE uplink characteristics, which was adopted as the consensus recommendation of the CSMAC LTE Technical Characteristics WGs for AWS-3 LTE uplink emission modeling. The recommendation included the following:

- Two UE Effective Isotropic Radiated Power (EIRP) curves (Urban and Rural) were provided
- Physical Resource Blocks (PRB) per Transmission Time Interval (TTI) occupation assumed to be 100%
- 3 UE/s per 5MHz of LTE uplink bandwidth (BW) per TTI

Beginning shortly after the AWS-3 assessment Initial Operating Capability (IOC), SSTD developed and has been improving an LTE Emission Ensemble Model (LEEM) that focused on the physical layer of an LTE network. In 2019 SSTD began collaborating with the AT&T SLS team to update the CSMAC 2012 recommendation. Improvements included:

- Improved modeling (AT&T SLS improved)
- Higher Fidelity Modeling (5 vs 2 macro morphologies)
- Support for LTE small cells (cochannel and non-cochannel)

In 2020, SSTD began an effort the leverage the results from the AT&T collaboration. SSTD began the development of an enhanced LEEM so that, as much as possible, it would take the same approach as the AT&T SLS. Validation of LEEM was performed by comparing key output statistics to those provided by AT&T for each of the simulations.

After validation, SSTD then used LEEM to generate new EIRP models using DoD requirements. Two key differences between the AT&T simulations and the LEEM simulations were:

- More realistic building exit loss model – ITU-R 2109
- More realistic scheduler – proportional fair without mods

In parallel with the EIRP distribution work, SSTD developed a new category model that would select the proper EIRP curve to use based on a given sector's estimated Inter-Site Distance (ISD) between LTE base stations and the antenna height. An approach using the sector's nearest neighbor within the horizontal beamwidth of the sector antenna was chosen.

Validation for the combined LTE emission model which incorporates UE EIRP, category, and network loading models was performed by comparing real-world measured data to Aggregate Interference (AI) predictions, using the new LTE emission model. Carrier Coordination Testing (CCT) events were used to measure real-world LTE emission data.

A. LTE Emission Model Description

In 2021, key AWS-3 stakeholders approved the following recommendation for LTE uplink emission modeling for AWS-3 spectrum sharing assessments.

UE EIRP Model - When determining the UE uplink EIRP for AWS-3 spectrum sharing:

- Incorporate 5 (based on an estimate of sector ISD) LTE macro-cell UE EIRP distributions
- For small cells (antenna height less than 10m):
  - Approve by rule cochannel small cells associated with approved AWS-3 macro cells.
    - Note that the aggregate interference from the combined small and macro cells is lower than the AI from the macro cell alone.
- Use the AT&T non-cochannel (NCH) one small-cell EIRP curve associated with 1732 meter ISD macro cell for “standalone” small cells.

The UE EIRP Cumulative Distribution Functions (CDFs) are shown in Figure 2 and Table. 1. CSMAC Urban and Rural curves are shown for reference.

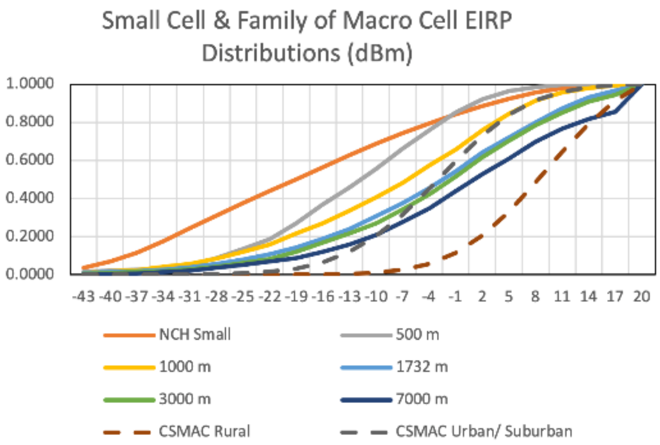


Fig. 2. UE EIRP CDF Curves

Table 1. UE EIRP CDF VALUES

CDF of Total EIRP per Scheduled User Equipment								
EIRP (dBm)	NCH Small	500 m	1000 m	1732 m	3000 m	7000 m	CSMAC Rural	CSMAC Urban/ Suburban
-43	0.0370	0.0153	0.0093	0.0087	0.0052	0.0026	0.0000	0.0000
-40	0.0690	0.0210	0.0183	0.0149	0.0089	0.0034	0.0000	0.0000
-37	0.1160	0.0265	0.0237	0.0190	0.0161	0.0067	0.0000	0.0001
-34	0.1760	0.0370	0.0422	0.0273	0.0193	0.0140	0.0000	0.0003
-31	0.2430	0.0521	0.0573	0.0391	0.0279	0.0205	0.0000	0.0011
-28	0.3110	0.0865	0.0848	0.0557	0.0414	0.0358	0.0000	0.0031
-25	0.3770	0.1344	0.1197	0.0800	0.0612	0.0515	0.0000	0.0071
-22	0.4390	0.1860	0.1588	0.1079	0.0827	0.0681	0.0002	0.0154
-19	0.5000	0.2693	0.2163	0.1430	0.1210	0.0879	0.0006	0.0320
-16	0.5640	0.3683	0.2684	0.1876	0.1692	0.1199	0.0013	0.0647
-13	0.6260	0.4561	0.3347	0.2390	0.2159	0.1588	0.0039	0.1194
-10	0.6880	0.5546	0.4064	0.3086	0.2706	0.2096	0.0099	0.2033
-7	0.7440	0.6630	0.4831	0.3764	0.3435	0.2760	0.0252	0.3161
-4	0.7950	0.7596	0.5727	0.4536	0.4221	0.3478	0.0577	0.4531
-1	0.8420	0.8528	0.6580	0.5426	0.5163	0.4384	0.1152	0.5960
2	0.8850	0.9207	0.7574	0.6431	0.6158	0.5278	0.2063	0.7299
5	0.9240	0.9634	0.8448	0.7214	0.7037	0.6092	0.3308	0.8393
8	0.9560	0.9850	0.9121	0.7980	0.7833	0.6986	0.4844	0.9146
11	0.9780	0.9957	0.9566	0.8726	0.8488	0.7663	0.6449	0.9596
14	0.9910	0.9989	0.9800	0.9308	0.9093	0.8159	0.7922	0.9832
17	0.9960	0.9998	0.9932	0.9669	0.9445	0.8555	0.9125	0.9938
20	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

If equivalent (mean) EIRP is used in the analysis, use the mean EIRP for the 5 macro-cell categories and the non-cochannel (NCH) small-cell category as shown in the Table 2.

Table 2. MEAN EIRP FOR DIFFERENT ISDS

ISD	FY21 Mean EIRP (dBm)
NCH Small Cell	2.38
500 m	-2.23
1000 m	4.12
1732 m	8.20
3000 m	9.25
7000 m	12.01

Macro-Cell Category Model - The “Nearest Neighbor” approach is used for the selection of LTE Emission category for macrocells. This model depends on having a complete list of sectors. The nearest neighbor is the closest macro cell that is within the antenna horizontal full 3 dB beamwidth. If there is no nearest neighbor within 20 km in the coverage direction of the antenna horizontal beamwidth, select the nearest neighbor without regard to the antenna pointing direction. Table 3 maps the sector radius (half the distance to the nearest neighbor) to the ISD category bins.

Table 3. SECTOR RADIUS TO CATEGORY MAPPING

Sector Radius (m)	ISD Category (m)
<=375	500
(375, 683]	1000
(683, 1183]	1732
(1183, 2500]	3000
>2500	7000

Network Loading Model - The Network Loading (NL) value for each specified category uses a morphology-based category model where Urban/Suburban or Rural is defined by the US Census Bureau’s Urban shapefile and is provided for two choices for the number of simultaneous emitting UEs in a sector. The number of simultaneous emitting UEs in a sector is a matter of preference. The average aggregate interference for both options is the same.

- When using 3 UEs per 5 MHz of uplink bandwidth:
  - Rural: NL= 16%
  - Urban/Suburban: NL= 26%
- When using 2 UEs per 5 MHz of uplink bandwidth:
  - Rural: NL= 24
  - Urban/Suburban: NL= 39%

B. *Current and Future Work*

The ongoing SSTD LTE characterization efforts on SSTD include several key items.

Advanced Emission Models - Sector-based LTE characterization models have an advantage over UE-based models because they can directly address the behavior of the LTE uplink scheduler and the relationship amongst the UEs scheduled in the same subframe. Two sector-based emission models have been under development in SSTD.

- Pathloss-Based Sector Uplink Emissions Model (PBSUEM) is a model for predicting AI in AWS-3 bands using a sector-centric architecture. PBSUEM assumes each LTE sector can be classified into five different ISDs. Each ISD category has its own parameters for modeling the total sector EIRP generated by uplink (UL) traffic within the sector.

- Greenman Sector Emission model (Greenman) which is also a sector-based emission model uses only a few key pieces of information about base station antennas in an LTE deployment, to predict total sector interference power after the uplink emissions have cleared the local clutter field.

Improved UE Emission Models - Improvements to LEEM are focused on the following outputs.

- A new NCH small cell uplink emission model that uses a more realistic scheduler and building exit loss model as compared to the one used by AT&T's SLS team.
- An indoor Distributed Antenna System (iDAS) uplink emission model that captures how sectors with indoor base station antennas generate interference experienced by DoD systems.

Gaussian Mixture Model (GMM) for Sector Path Loss - This work uses a GMM method on data from 8 cellular markets within the contiguous United States to identify naturally occurring classes of the pathloss distributions and then relates the parameters of sectors in the proposed cellular network to the expected interference generated from each sector.

IV. PROPAGATION MODELING

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 effects, clutter is perhaps the most complex and by extension the most difficult to assess. Because of the slant ranges associated with AWS-3 early-entry analyses the path loss effects of clutter are usually significantly less than those due to distance, terrain, or atmosphere. This combined with DoD's well-established models of terrain and atmospheric propagation effects, led to the current approach which is to use existing 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.

A. Terrain and Atmospheric Propagation Models

Atmospheric propagation loss modeling incorporates a DoD receiver antenna height-based category model. For DoD receiver antenna heights greater than 5,000 feet above-ground-level (AGL), classified as ground-to-air, IF-77, using terrain profiles from a digital terrain model (DTM) is used. Prior to adopting IF-77 as the ground-to-air model, ITU R-REC-P.528-3, a derivative of IF-77 was used. The need to interpolate amongst the provided curves and the lack of consideration for terrain interactions like those that occur from mountain ranges, led to the adoption of IF-77.

For DoD system antenna heights less than or equal to 5,000 feet AGL, classified as ground-to-ground, TIREM with terrain profiles from a DTM is used. Note that even though drones are aircraft, many have a maximum antenna height below 5,000 feet AGL and as such use the ground-to-ground propagation loss model.

B. Terrain Data

The terrain data used in both terrain and atmospheric propagation models is taken from United States Geological Survey (USGS) Digital Elevation Model (DEM) Level 2 data. This data set has a resolution of 30 meters, is freely available for the entire US, and is continuously updated by USGS. Prior to adopting this data set, DoD Digital Terrain Elevation Data (DTED) Level 1 data was used, which has a 90-meter resolution.

C. Clutter Loss Propagation Model

Clutter loss modeling has been one of the most active areas of research for SSTD. The approach for improving clutter loss modeling begins with the development of techniques that estimate clutter loss for a given scenario. Once a technique has been validated using measured data, a set of clutter site assessments (CSAs) is performed. For each elevation angle of interest, a CSA generates up to 3200 path loss estimates using 200 UE positions and 16 receiver positions for a given clutter site. The most recent SSTD clutter loss modeling work included the use of over 4000 CSAs. From each CSA, a process called feature augmentation is conducted that adds various morphology and clutter height data to each CSA. The augmented CSAs are then grouped into categories based on their feature set. In the final step, the clutter loss distributions for each category are created by combining the clutter loss estimates for each member site's CSA in that category.

Clutter Category Modeling - The left side of Figure 3 provides a visualization for the initial 4-category clutter model. Categories were selected by DoD receiver antenna height and morphology as determined by the US Census Bureau Urban shape file. The right side of Figure 3 depicts the current 117-category model where morphology as determined by the USGS National Land Cover Database (NCLD) dataset, elevation angle from a UE to the DoD receiver, and average clutter height are used.

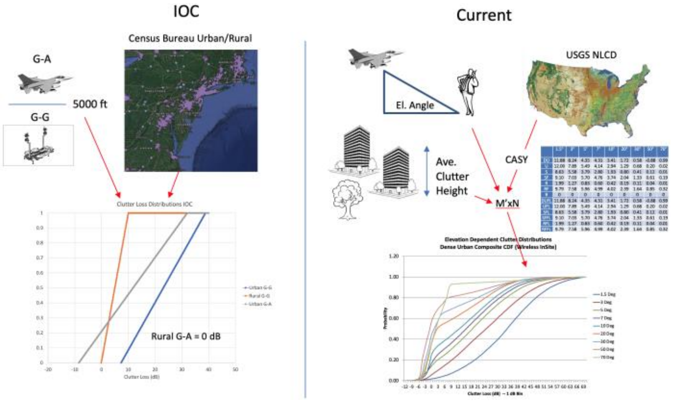
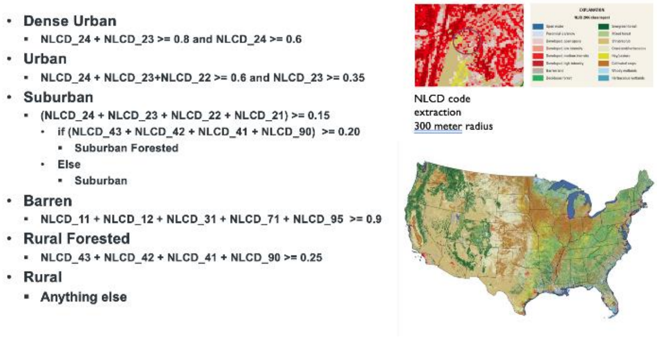


Fig. 3. Evolution of Clutter Loss Modeling

The morphology model (named CASY) is depicted in Figure 4 and uses the percentage of key NLCD codes found within 300 meters of a site along with a b-tree algorithm to select a clutter morphology.



- Dense Urban
  - NLCD_24 + NLCD_23 >= 0.8 and NLCD_24 >= 0.6
- Urban
  - NLCD_24 + NLCD_23+NLCD_22 >= 0.6 and NLCD_23 >= 0.35
- Suburban
  - (NLCD_24 + NLCD_23 + NLCD_22 + NLCD_21) >= 0.15
    - if (NLCD_43 + NLCD_42 + NLCD_41 + NLCD_90) >= 0.20
      - Suburban Forested
    - Else
      - Suburban
- Barren
  - NLCD_11 + NLCD_12 + NLCD_31 + NLCD_71 + NLCD_95 >= 0.9
- Rural Forested
  - NLCD_43 + NLCD_42 + NLCD_41 + NLCD_90 >= 0.25
- Rural
  - Anything else

Fig. 4. Clutter Loss Morphology Model

The average clutter height is assessed by comparing the DTM and digital surface model (DSM) layers of a 5-meter resolution elevation data set for each site. All morphology categories except for Barren, have a flat (low average clutter height) and non-flat (higher average clutter height) selection. Table 4 has the flat/non-flat clutter height thresholds.

Table 4. CLUTTER HEIGHT THRESHOLDS

CASY Clutter Category	**Average Clutter Height Threshold (m)**
Dense Urban	3.1
Urban	1.6
Suburban	1.3
Suburban Forested	5.7
Rural	0.3
Rural Forested	3.9
Barren	N/A

Table 5 provides Equivalent Clutter Loss (ECL) values for each of the 117 clutter loss distributions used on the most recent AWS-3 clutter modeling recommendation. The ECL is the clutter loss value that can be used in lieu of a clutter loss distribution if aggregate interference is not modeled as a random variable.

Table 5. ECL VALUES

Clutter Loss ECL (dB)	**Elevation Angle**								
Clutter Morphology Category	**1.5°**	**3°**	**5°**	**7°**	**10°**	**20°**	**30°**	**50°**	**70°**
Dense Urban Flat	9.51	6.93	5.81	4.72	3.57	2.56	1.83	1.56	2.47
Dense Urban Non-Flat	13.53	11.41	9.47	8.25	6.85	5.09	3.93	3.11	3.74
Urban Flat	9.85	7.39	5.35	4.12	3.01	1.43	0.79	0.24	0.02
Urban Non-Flat	11.84	8.93	6.58	5.19	3.93	2.05	1.27	0.51	0.11
Suburban Flat	3.95	2.89	2.13	1.70	1.31	0.70	0.43	0.14	0.02
Suburban Non-Flat	10.16	7.59	5.68	4.52	3.42	1.78	1.09	0.44	0.11
Suburban Forested Flat	9.58	7.89	6.31	5.26	4.21	2.55	1.76	0.84	0.22
Suburban Forested Non-Flat	13.99	11.18	8.99	7.52	6.03	3.57	2.45	1.23	0.40
Rural Flat	0.45	0.34	0.29	0.26	0.24	0.21	0.14	0.03	0.00
Rural Non-Flat	3.06	2.07	1.49	1.21	0.95	0.60	0.44	0.19	0.04
Rural Forested Flat	3.27	2.86	2.51	2.32	2.11	1.72	1.41	0.77	0.24
Rural Forested Non-Flat	9.66	7.48	5.93	4.98	4.09	2.66	1.99	1.16	0.43
Barren	0	0	0	0	0	0	0	0	0

D. *Current and Future Work*

The ongoing SSTD improved propagation efforts include several key items.

<u>Expanded and Improved CSAs</u> - This effort will expand the geospatial data set needed to acquire more CSAs as well as add improved foliage and multi-path propagation models to the CSA generation techniques.

<u>Machine Learning</u> - This effort uses unsupervised machine learning methods to learn new categories of clutter models. In addition, a predictive model that provides a fast site-specific clutter loss distribution from US-wide geospatial feature data is under development. For more information see ISART 2022 paper - *A Comparison of Data-driven Clutter Loss Clustering Models for New Site Interference Assessment*.

V. DOD RECEIVER CHARACTERIZATION

When considering the impact to a DoD system/receiver operating in the presence of aggregate interference from a field of UEs, both electrical characteristics and the operational parameters for the system/receiver must be considered. DoD system IPCs and receiver selectivity curves are used to address the electrical characteristics. Spatial parameters derive from operational scenarios.

A. *Consider Desired Signal*

In the absence of reliable information regarding desired signal levels, an approach to establishing the IPC for a receiver uses the comparison of the interference power to the noise floor of the receiver. At IOC an Interference to Noise Ratio (I/N or INR) of -6 dB was established as the IPC for many AWS-3 DoD receivers. This IPC is likely conservative in many cases and can be relaxed once a worst-case operational Signal to Interference plus Noise Ratio (S/(I+N) or SINR) analysis can be performed to give a more realistic value.

In order to have a common approach for evaluating spectrum sharing for all DoD systems, an approach for mapping SINR to INR was developed. Using this approach, as more and better information became available, less conservative IPCs were employed without the need to update the tools used to assess sharing.

INR to SINR Mapping Assumptions - In general, this analysis requires that the interference source, which is LTE uplink emissions for AWS-3, cause noise-like degradation to the receiver.

- The aggregate interference from many devices will likely appear noise-like
- Interference channel bandwidth is wider than receiver bandwidth
- Partial interference channel utilization will likely appear noise-like

<u>Methodology</u> - The general methodology for performing the mapping is depicted in Figure 5. The high-level description is:

- Verify that interference will cause noise-like degradation to the receiver
- Determine the system receiver required signal power (Sreq)

  - Receiver sensitivity or Minimum Detectable Signal (MDS)
- Generate a link budget to calculate the expected worst-case operational desired signal power (Sop) at the receiver based in part on the distance between the transmitter and the receiver
- Determine if worst-case operational signal power, Sop, provides margin over minimum required signal power, Sreq
- If margin is available, perform S/(I+N) analysis
- Use worst-case operational S/(I+N) and receiver S/N specification to calculate associated I/N (hereafter referred to as adjusted $(I/N)_{th}$)

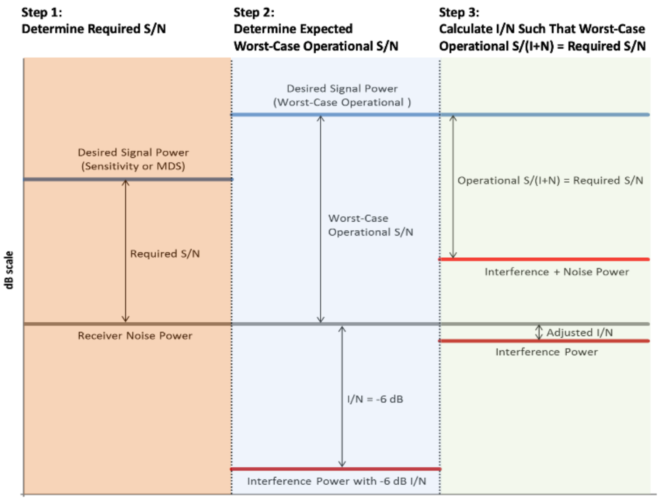


Fig. 5. SINR -> INR Mapping

Approach - The approach to performing the SINR -> INR mapping is:

1. Set the expected worst-case operational S/(I+N) equal to receiver required S/N (both as ratios)

$$\frac{S_{op}}{I+N} = \frac{S_{req}}{N} \tag{1}$$

Where:

- Sop is the expected worst-case operational desired signal power at the receiver, in mW
- Sreq is the required signal power at the receiver (sensitivity or MDS), in mW
- N is the rreceiver noise power, in mW
- I is the iinterference power at the receiver, in mW

2. Solve for I

$$I = N\left(\frac{S_{op}}{S_{req}} - 1\right) \tag{2}$$

3. Calculate adjusted $(I/N)_{th}$

$$\left(\frac{I}{N}\right)_{th} = \frac{N\left(\frac{S_{op}}{S_{req}}-1\right)}{N} \tag{3}$$

$$\left(\frac{I}{N}\right)_{th} = \frac{S_{op}}{S_{req}} - 1 \tag{4}$$

4. The adjusted $(I/N)_{th}$, in dB (INR_{th})

$$INR_{th} = 10Log_{10}\left[10^{\left(\frac{S_{op(dBm)}-S_{req(dBm)}}{10}\right)} - 1\right] \tag{5}$$

B. Polarization

Antenna polarization for UEs and DoD receivers can introduce loss when considering interference power levels. A minimum loss (0 dB) occurs when the phone and DoD receiver polarizations are aligned, and a maximum loss (∞ dB) occurs when they are orthogonal (for linear polarization). Figure 6 shows an illustration of polarization rotation.

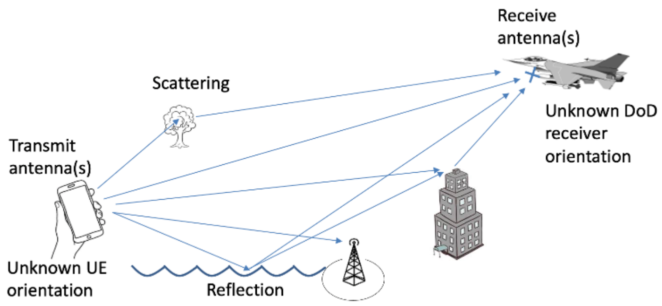


Fig. 6. Example Polarization Rotation

At IOC a default assumption of 0 dB polarization loss was used. The random nature of the UE and DoD receiver orientations along with scattering and reflection in the environment leads to the conclusion that the polarization alignment necessary for 0 dB or no polarization loss is unlikely. A survey of UE and DoD receiver antenna polarization and an assessment of relative antenna orientations was conducted in pursuit of a more realistic polarization loss model.

Antenna Polarization - A study of typical UE antenna configurations finds that linear polarizations are used and Table 6 describes the polarizations used by DoD receivers in the AWS-3 band.

Table 6. AWS-3 DOD ANTENNA POLARIZATION

DoD System	Vertical (V)	Horizontal (H)	Horizontal and Vertical (H&V)	Linear (L)	Right-hand Circular (RHC)	Left-hand Circular (LHC)
ACTS	✓	✓	✓			
Video	✓		✓	✓		
Telemetry	✓				✓	✓
Robotics	✓		✓		✓	
SUAS	✓			✓		
TTC					✓	
TRR	✓	✓	✓	✓		
Microwave	✓	✓				

JTRS WNW	✓					
TTNT	✓			✓		

By assumption, the relative orientation between a UE linearly polarized antenna and a DoD linearly polarized antenna is uniformly distributed between -180 to +180 degrees.

Polarization Loss Assessment - Figure 7 illustrates the angular difference and loss statistics between a UE and a DoD receiver with a linearly polarized antenna. It is assumed that that angle will be random over [-180, 180] for UEs and DoD receivers that use linear polarization. The plot illustrates the polarization loss as modeled in 1 million trials where the angular difference is randomly chosen. The mean loss is 3 dB.

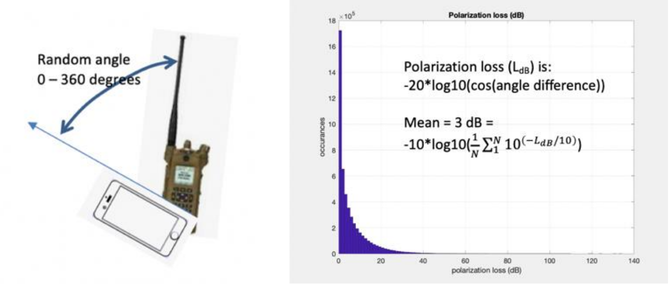


Fig. 7. Angular Difference and Loss Statistics

Table 7 gives the recommended LTE UE to DoD receiver polarization loss values based on polarization type.

Table 7. POLARIZATION LOSS VALUES BY TYPE

DoD Receiver Antenna Polarization Type	Average Loss (dB)
Horizontal	3
Vertical	3
Linear	3
Circular	3
Horizontal and Vertical	0.87

C. *Current and Future Work*

The ongoing SSTD Receiver Characterization efforts on SSTD are focused on improved mission assessments. In this work, DoD systems performance using real operational scenarios are assessed when sharing spectrum with commercial wireless systems. Expansion of the previous SINR work to include operational geometries and system resilience to interference are considered.

VI. AGGREGATE INTERFERENCE MODELING

The DoD assessment of the impact to DoD operations from a CR begins with a comparison between the expected interference power from the LTE sectors in the carrier's CR, to each DoD system who's CZ includes those sectors. The total interference power that a DoD system can receive, without impact to operations is defined by the system's 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 all LAs that overlaps the CZ. The portion of the IPC-specified interference power allocated to a LA, for each DoD system, is used to assess a CR for the LA.

A. *Modeled UE Interference Power*

Currently, DoD 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 Equation (6).

$$I_k = NL(P_{Tx}) + EIRP(P_{Tx}) - L_{Cl}(P_{Tx}) - L_p(P_{Tx}, P_{Rx}) - FDR(\Delta f) + G_r(\theta, \phi) - L_{pol} - L_s \qquad (6)$$

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 average 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 (7) 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 from the CR until the IPC for the LA is not exceeded.

$$i_{total} = \sum_{k=1}^{N} 10^{\frac{I_k}{10}} \tag{7}$$

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

B. *IOC Aggregating Interference Approach*

Two fundamental questions emerge when assessing a CR:

- How much of the total interference power can be allowed from sectors in the LA?
- If aggregate interference is modeled as a random variable, what is the confidence interval that should be used for that LA?

At the onset of the AWS-3 CR business process, a margin apportionment process is performed for determining how much interference power can be tolerated from each LA to each DoD receiver, known as a Spectrum Access Record (SAR), and the appropriate confidence interval to use. This margin apportionment process includes:

1. Use a proxy for a nationwide LTE base station laydown
2. Separately for each SAR, remove all base stations within the areas of operation (AO) of the DoD Receiver.
3. Looking at a set of probe points along the perimeter and within the AO, using a common AI model, iteratively calculate the AI from all LTE towers, removing the biggest interferer each time, until each probe point is below the IPC for the DoD receiver.
4. Count the towers that remain in the laydown and allocate to each LA a percentage of the total IPC power calculated from the remaining towers in the LA divided by the total towers remaining.
5. The initial approach to establishing a per LA confidence interval was simply to use the system confidence interval for each.

C. *Aggregating Interference Issues*

The original approach to margin apportionment had the following issues*:*

- <u>Link-Budget Equivalency</u> - Not all stakeholders calculated AI in the same way so when a stakeholder's margin calculation is different from the AI calculation the combination is internally inconsistent.
- <u>Superposition</u> - The approach, illustrated in Figure 8, implies superposition for the DoD receiver. In other words, it assumes that the DoD receiver is simultaneously located at all probe points when determining its received interference power.

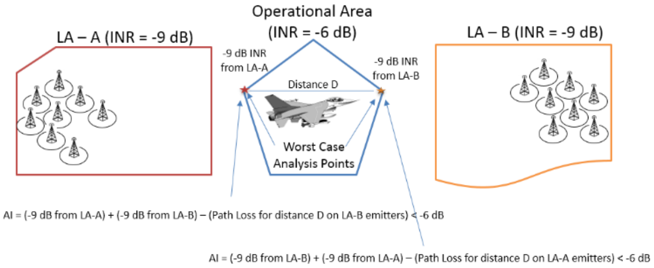


Fig. 8. Illustration of Superposition Issue

- <u>Biased Margin Apportionment</u> - The approach uses a count of towers, instead of the interference power from each tower when divvying up margin.
- <u>Orphaned Towers</u> - The approach reduces the margin for LAs straddling the edge of the CR by not including towers outside the CZ during margin apportionment but including them in the business process AI assessment.
- <u>Multi-SAR</u> – sectors removed by one SAR should not be considered as present when assessing other SARS for the purposes of establishing a field of permitted interferers
- <u>Confidence Interval</u> – As shown in Figure 9, if the probability that two LAs are expected to exceed their individual IPCs is 10%, then the probability that the combined LAs will exceed the sum of the two IPCs is less than 2%. The per LA confidence interval must be reduced below the aggregate AI confidence interval to achieve the desired value.

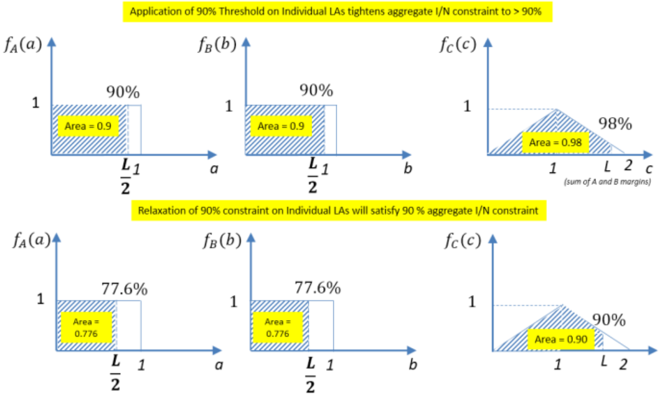


Fig. 9. Illustration of Confidence Interval Issue

D. *Aggregating Interference Improvements*

A perfect approach to aggregating interference would require a priori knowledge of the LTE sector laydown. Since this is not possible the best available proxy should be used. Once a nationwide laydown is established the process of margin apportionment should use the actual interference calculation for each interferer to identify the set of interferers whose total power is less than each SAR's IPC. At this point the total power from each LA observed at each probe-point for each SAR can be calculated. These power-position pairs should then be used when evaluating a CR.

When AI is modeled as a random variable this approach should be used.

1. Use a proxy for a nationwide LTE base station laydown.
2. For all SARs, remove all base stations within the AO and outside the CZ of the DoD receiver.
3. Looking at a set of probe points along the perimeter and within the AO, using a stakeholder-specific AI model, iteratively calculate the AI from all towers, removing the biggest interferer each time, until each probe point is below the IPC for the DoD receiver.
4. Add the power for surviving towers in the laydown for each SAR/LA/probe-point tuple.
5. Use the following approach to calculate the best confidence interval for each tuple.
    a. Select an analysis point in the SAR.
    b. Assume the total margin apportioned to all of the LAs encumbered by the SAR is expressed as M in linear units and the margin apportioned to LA i at this selected analysis point is expressed as M_i in linear units.
    c. Let α_i be the fraction of total margin apportioned to LA i i.e., $\alpha_i = \frac{M_i}{M}$ at the selected analysis point.
    d. Compute the confidence interval ($C_{i,}$) associated with α_i according to this equation (analytically-computed confidence interval):

$$C_{i,} = \Phi[\sqrt{\alpha_i}\Phi^{-1}(C)] \tag{8}$$

where Φ is the CDF of a Gaussian random variable with a mean of 0 and variance of 1 (standard normal distribution) and C is the confidence interval for the SAR e.g., 90%.

Note that under certain scenarios the computed per LA confidence interval may result in an aggregate confidence interval that is slightly below the target. If this is a concern an optimization algorithm has been developed that adjusts the confidence intervals and ensures the target is always met.

VII. MEASUREMENTS AND DATASETS

High-quality measurements and any other ground-truth data about the real world are the lifeblood of any model development effort that seeks to make reliable predictions. The SSTD program engages in several efforts, across the program's initiatives, to collect measured data that directly aids AWS-3 spectrum sharing model development.

A. Characterizing LTE

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 phones. 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.

- To date, 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 (DAS) sectors in buildings, a conference center, and a stadium.

LTE Lab Measurement Systems – SSTD has developed and is using automated lab measurement systems with The MITRE Corporation and the National Advanced Spectrum and Communications Test Network (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.

- The MITRE Multi-UE Test Bed (MULE) provides detailed information about every UE's emission within the emulated sector, including the TTI and PRBs occupied by each emission as well as the MCS and TBS. The reported RSRP of each UE is also recorded in a separate file. Data for the following emulations is available.
    - Longmont 5PM, heavy traffic time on all sectors
    - Longmont 6AM, low traffic time on all sectors
    - Cell Radius Study – for each of the 5 cell radii and 2 morphologies (urban and rural)
    - Cell Radius Study, limiting pmax to 10dBm
- The National Advanced Spectrum and Communications Test Network (NASCTN) conducted an SSTD sponsored project to Characterizing User Equipment Emissions. The effort produced three publications and sets of data that are available at nist.gov:
    - NIST Technical Note 2056: Antenna Pattern Measurements (https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.2056.pdf)
    - NIST Technical Note 2069: Factor Screening Experiment (https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.2069.pdf)
    - NIST Technical Note 2147: Closed-Loop Power Control Experiment (https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.2147.pdf)

Commercial Wireless AWS-1 Multi-market Data - SSTD has an ongoing collaboration with AWS-3 licensees to collect AWS-1 Key Performance Indicator (KPI) and sector configuration data from a large sampling of LTE deployments.

- LTE sector configuration, KPI, and distance histogram data for 8 US markets or an 8-day period in February of 2020 has been collected for Albuquerque, NM; Blacksburg, VA; Charleston, SC; Denver, CO; Idaho Fall, ID; Los Angeles, CA; San Diego, CA; and Washington, D.C.
- LTE sector configuration, KPI, and distance histogram data covering the time periods where SSTD Aggregate Inference measurement events have been acquired. Sites include Longmont, CO; Grand Junction, CO; Boulder, CO; Denver, CO; Salt Lake City, UT; and Charlottesville, VA.

B. Terrain/Atmospheric Propagation Effects

FAA ADS-B Data - FAA's new aircraft collision and avoidance system infrastructure, Mode-S, is a communication system set in place by FAA to serve as a next generation-self-reported radar-like system and is 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.

- ADS-B message data along 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, ~50 million flight hours.
- (Future) PostGIS relational database that extracts and organizes propagation relevant data for each ADS-B received message, assuming an average path length of 150 km ~60 light years of air-to-ground propagation path data.

Direct Measurement GPS - SSTD performers are developing a prototype system that simultaneously measures Global Positioning System (GPS) received signals at two locations: one location inside a clutter field or inside a building and the other in an open area with line-of-sight to the GPS satellite. This system looks at the difference in receive power to assess the effects of clutter/building losses. Measurement for high elevation angles is also possible with this technique.

Direct Measurement ADS-B - SSTD performers are developing a prototype system that simultaneously measures ADS-B signals at two locations: one location inside a clutter field or inside a building and the other in an open area with line-of-sight to the transmitting aircraft. This system looks at the difference in receive power to assess the effects of clutter/building losses. Measurement for high elevation angles is also possible with this technique.

Propagation Drive Tests - For over seven years SSTD has been working with propagation measurement teams, including NTIA's Institute for Telecommunication Sciences (ITS) to conduct high-quality measurements at AWS-3 adjacent frequencies, e.g., 1780 MHz that can support estimates of propagation losses including those due to clutter.

- Thus far, SSTD has used both a ground-ground and a ground-to-air propagation measurement system to collect over 1 million discrete measurements throughout the US in all morphologies and for elevation angles up to 50 degrees.
- (Future) PostGIS relational database that contains normalized measurements along with associated feature data. Feature data includes information on path characteristics, morphology, and clutter height around the measurement.

C. Aggregate Interference

SSTD has also been working with LTE uplink measurement teams, including NTIA/ITS and others to conduct high-quality measurements that can support validation and verification of AWS-3 aggregate interference models. Thus far, SSTD has used both a ground-based and a drone-based measurement system to collect emissions from Longmont CO, Grand Junction CO, Boulder CO, Denver CO, Salt Lake City UT, and Charlottesville VA. This data along with the LTE operational data allows research to assess and improve all models used in predicting aggregate interference.

VIII. CONCLUSIONS

This paper provided an overview of the AWS-3 SSTD program's most current findings relative to AWS-3 spectrum sharing assessments. Analytical model descriptions that are used for AWS-3 commercial wireless emissions; terrain, atmospheric, and clutter propagation loss; and DoD victim receiver characterization are described along with interference power aggregation and partitioning models. SSTD measurements and data sets are also described. Findings and data described in this paper 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. SSTD activities have resulted in improved capabilities for interference modeling to support greater commercial access to the 1755-1780 MHz frequency band while protecting DoD missions from interference from commercial LTE networks. SSTD findings are focused on AWS-3 spectrum sharing but are also applicable to other spectrum sharing scenarios. For more information regarding AWS-3 spectrum sharing or SSTD contact Joy Cantalupo Defense Spectrum Organization DISA Annapolis, MD, USA josephine.m.cantalupo.civ@mail.mil.

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