National Advanced Spectrum and Communications Test Network (NASCTN)

Trusted Spectrum Testing
5G Spectrum Sharing Testbed

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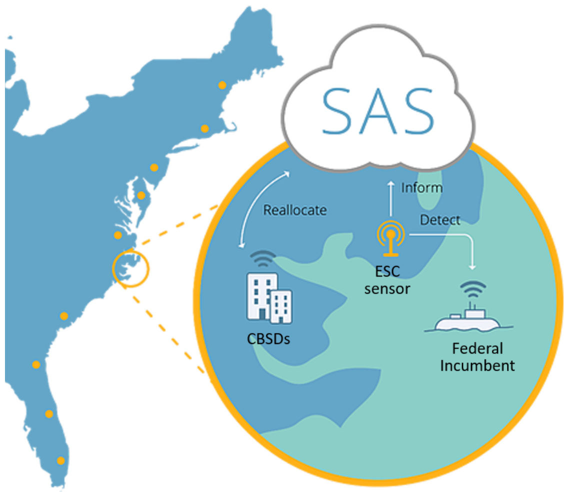
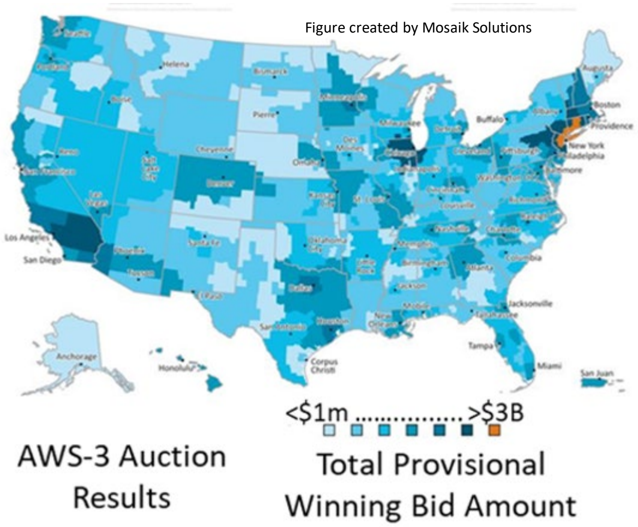
Growing Need for Trusted Spectrum Testing

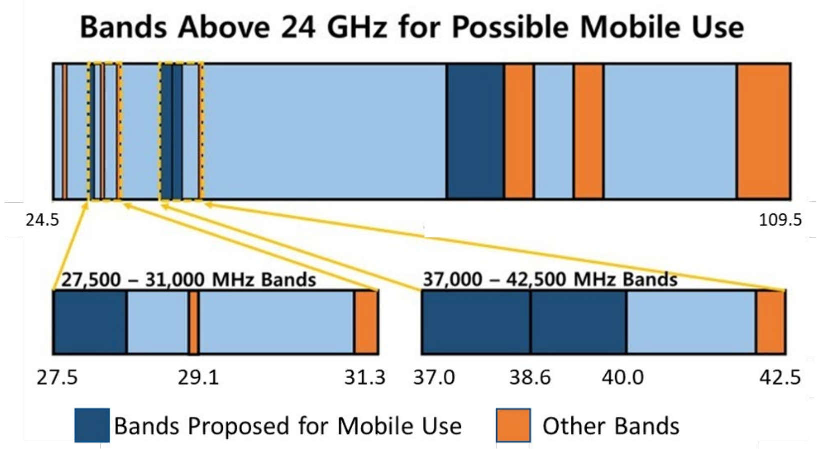
The Federal government is required to operate in a compressed spectrum ranges due to FCC auctions. This presents a risk that a variety of commercial and federal operators will harmfully interfere with each other.



Citizens Broadband Radio Service
CBRS (3.5GHz)
Navy Radars



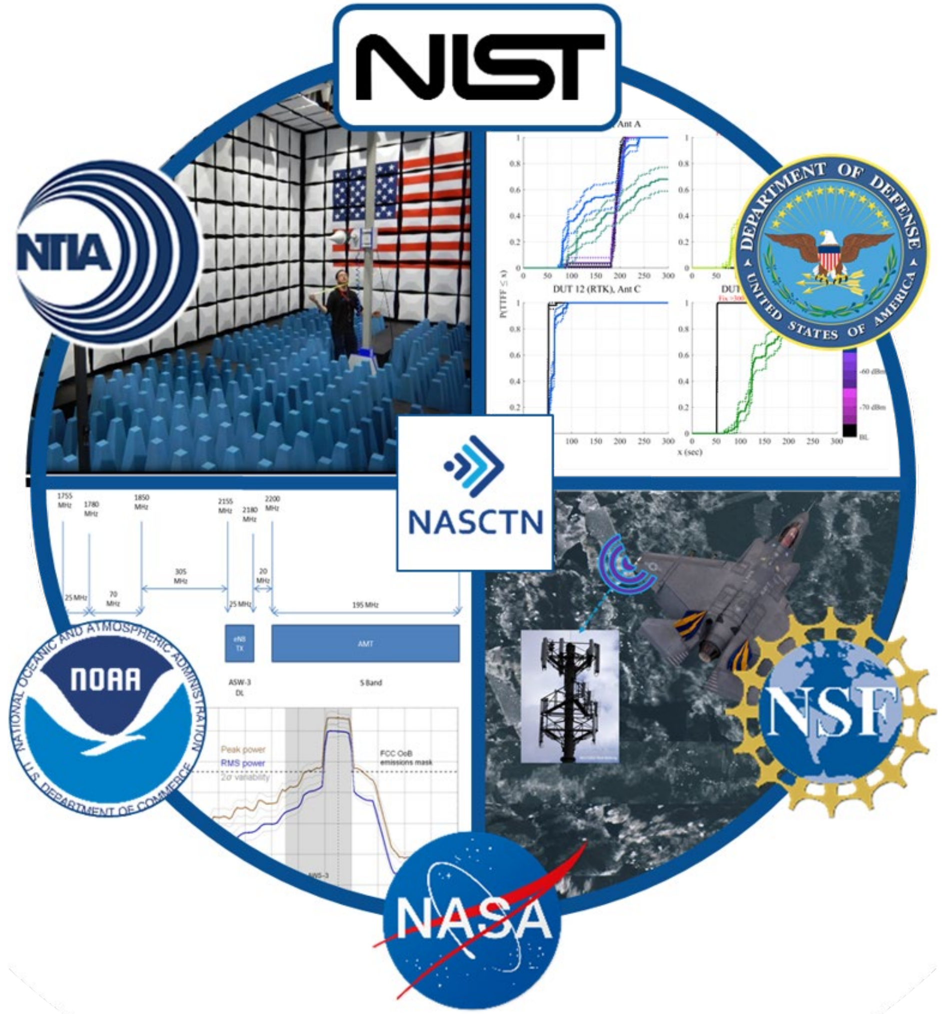
Advanced Wireless Services
AWS-3 (LTE)
DoD test ranges



Spectrum Frontiers (24&28GHz)
NASA/NOAA Weather
and remote sensing

National Advanced Spectrum and Communications Test Network (NASCTN)

NIST



- Established in 2015 by NIST, the U.S. DoD, and NTIA. In 2018, added NOAA, NSF, and NASA.
- Organizes a national network of federal, academic, and commercial test facilities
- Provides trusted spectrum testing, modeling, and analysis to develop and deploy spectrum-sharing technologies and inform future spectrum policy and regulations.

NASCTN MISSION

NIST

To provide, through its members, **robust test processes** and **validated measurement data** necessary to develop, evaluate and deploy spectrum sharing technologies that can **increase access to the spectrum** by both federal agencies and non-federal spectrum users.

- Develop scientifically rigorous test plans and new methodologies with independent experts
- Access to key test facilities, and commercial and federal equipment and capabilities
- Provide validated data and models for use within the spectrum sharing community

Operates as a trusted agent and protect proprietary, sensitive, and classified information

NASCTN Framework

NASCTN projects follow an open, transparent and comprehensive process for developing *independent*, scientifically based test plans, facilitating access to member test ranges and laboratories, protecting controlled information, and validating test results before findings are reported.

The five-stage Framework serves as a common architecture across NASCTN's projects.

NASCTN FUNDED		SPONSOR FUNDED		
STAGE 1 Project Request Screening	**STAGE 2** Test Framework "Tiger Team"	**STAGE 3** Test, Methodology, Implementation Plans	**STAGE 4** Execute Test	**STAGE 5** Summarize and Document Findings
ACTION StCm: Receives and evaluates Project Requests **GOALS** Ensures project meets NASCTN criteria	**ACTION** Tech Team: Develops test framework, PMP, scope, expectations (time/$). Gains Community input. **GOALS** Provides detail, defined scope and approach for better informed decisions.	**ACTION** Tech Team: Conducts experiments for Design of Experiment and Test Plan. Community input. **GOALS** Sponsor input on scope & objectives, but Test Plan and Design developed independently by NASCTN.	**ACTION** Tech Team: Execute Test Plan. Periodic briefings to Sponsor and StCm.	**ACTION** Tech Team: Write and publish Test Report. **GOALS** Dissemination of results to public and interested parties.
	↑ *Community Input*	↑ *Community Input*		↑ *Community Distributed*

Projects and Research

NIST

Sharing – LTE Bands

AWS-3: Aggregate Emissions (DoD DISO)

Co-Channel interference (Navy)

LTE Impacts on Earth Ground Stations, POES satellites (NOAA – Stage 2)

Impacts on Federal and Commercial Systems

Sharing - 3.5 GHz Band

Citizens Broadband Radio Service (CBRS)

Detection of RF waveforms

Detection and Standards in Shared Spectrum environment

Adjacent Band - LTE

GPS (Ligado Networks, LLC)

AWS-3 LTE Out-of-Band Impacts on AMT (Edwards Air Force Base)

LTE impacts on Federal Systems

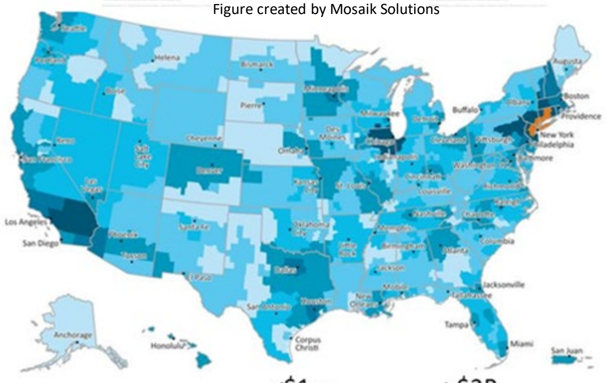
Projects: Outcomes and Impacts

NIST

Since NASCTN was founded in 2015, has pursued 6 key spectrum sharing projects that brought together Commercial and Federal agencies. These include:

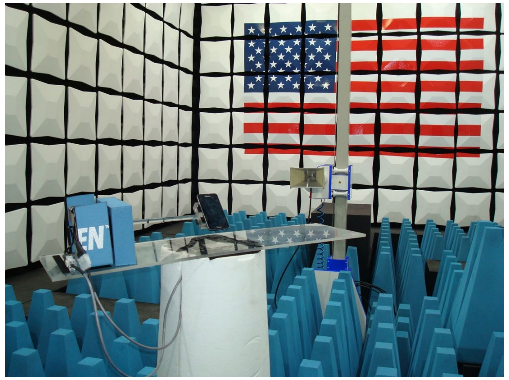
- **LTE Impacts on GPS L1** : Accepted as a neutral body and provided key data for LTE and GPS policy discussions. *(DoC Gold Medal)*
- **Aggregate AWS-3 LTE Emissions Project** : Informs interference models used by DoD for expedited and expanded entry of commercial deployments into the 1755-1780 MHz band. New metrology characterizes cumulative and complex interactions for cell phone emissions.
- **AWS-3 LTE Impacts on AMT**: Expands interference test methodology (beyond IRIG), and creates a public catalog of LTE waveforms for future interference testing for DoD test ranges to mitigate impact from future cellular equipment deployments.
- **Radar Waveforms in 3.5Ghz Band**: Collection of high resolution data. Machine Learning applied to IQ data and spectrographs provide methodology for occupancy rates, to inform commercial investments and risks.
- **AWS-3 LTE Out-of-Band Emissions:** Precise measurements for potential inference mitigation on DoD Range AMT systems.
- **Co-Channel Interference with LTE**: Test methodology for co-channel interference between advanced waveforms and LTE uplink traffic. Diverse KPIs to evaluate system response. *(Ex: hopping techniques degraded LTE performance despite high throughput.)*

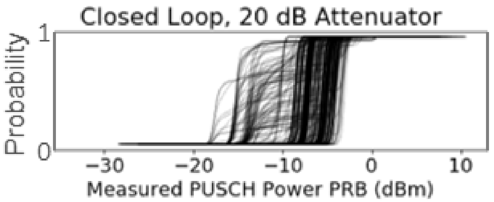
Aggregate AWS-3 LTE Emissions
(LTE Sharing)

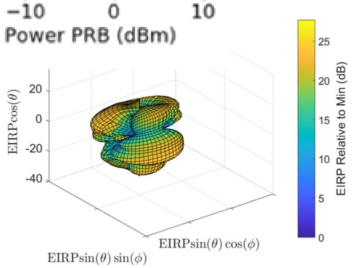


AWS-3 Auction Results

Total Provisional Winning Bid Amount







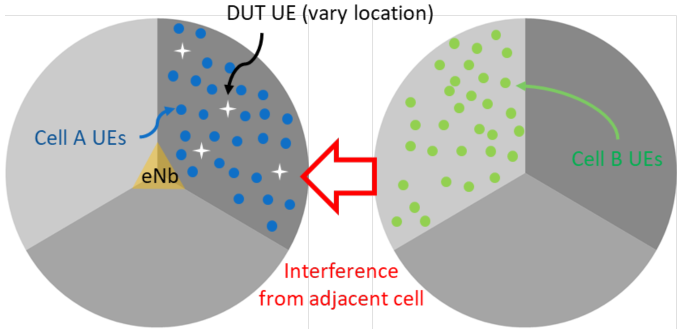
AWS-3 spectrum auction: $41.3B , must deploy within 5 years or lose license

Coordination for early entry relies on agreed upon Interference Model

Trusted rigorous measurement data required to inform proposed changes to Interference Model.   For Aggregate Emissions:
→ Factor screening
→ Characterization measurements on subset

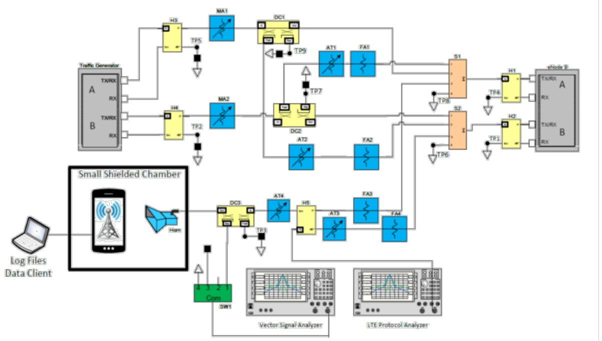
New metrology required to characterize cumulative and complex interactions for cell phone emissions.

Aggregate AWS-3 LTE Emissions
(LTE Sharing)



1) Cell A & Cell B loaded with UEs
2) Cell A UEs load eNB scheduler
3) Cell B UEs increase noise at eNB

- Vary position of DUT UE
- Combine data over entire cell to obtain statistics for particular config



Design of Experiment (DoE) - Factor Screening

- Evaluate all main effects, and some 2-factor interactions.
- Ensure main effects are uncorrelated
- Determine which factors have a significant impact (statistical analysis)

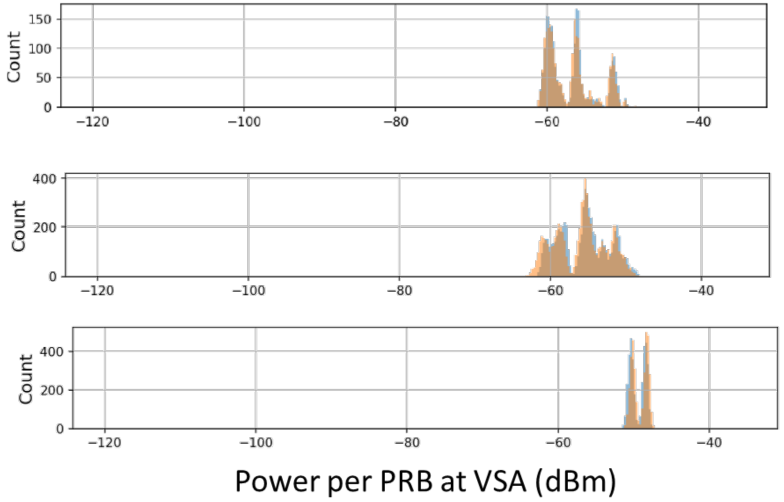
28 total factors: 8 non-eNB, 20 eNB

Identifer	Testbed Component	Factor	# Levels
A	Variable Attenuator	Path Loss (Simulated DUT UE Position)	2
B	UTG	Spatial Size of Cell	2
C	UTG	Number of Loading UEs in Serving Cell (Cell A)	2
D	UTG	Number of Loading UEs in Adjacent Cell (Cell B)	2
E	UTG	Spatial Distribution of Loading UEs in Cell A	2
F	UTG	QCI Value of Loading UEs	2
G	DUT UE/UTG	Traffic Data Rate	2
H	DUT UE/UTG	Traffic Type (UDP/TCP)	2
I	eNB	UL Scheduling Algorithm Type	3
J	eNB	UL Scheduler FD Type	3
K	eNB	Power Control Type (Closed Loop/Open Loop)	2
L	eNB	SRS Config	2
M	eNB	SRS Offset	2
N	eNB	PUCCH Power Control: P_0	2
O	eNB	PUSCH Power Control: P_0	2
P	eNB	Power Control: α	2
Q	eNB	Receive Diversity	2
R	eNB	Filter coefficient for RSRP measurements	2
S	eNB	Maximum uplink transmission power (own cell)	2
T	eNB	Minimum PRB allocation for power-limited UEs	2
U	eNB	UL Improved Latency Timer Reaction	2
V	eNB	Initial Max # of Resource Blocks	2
W	eNB	UL Link Adaptation	2
X	eNB	Extended Link Adaptation	2
Y	eNB	Cell Scheduling Request Periodicity	2
Z	eNB	Scheduling Weight UL for SRS	2
a	eNB	Blanked PUCCH Resources	2
b	eNB	Target UL Outer Scheduling	2

- 32-run design for eNB factors, crossed with a 32-run for non-eNB factors (Minimize eNb changes)
- Split-plot" design, randomized
- Run 4 times to maximize chance of conclusive findings
- Test Reference eNB config every day for baseline tracked over time
- Collected, Parsed and Synchronized data from 3 sources.

Design of Experiment (DoE) - Statistical Analysis:

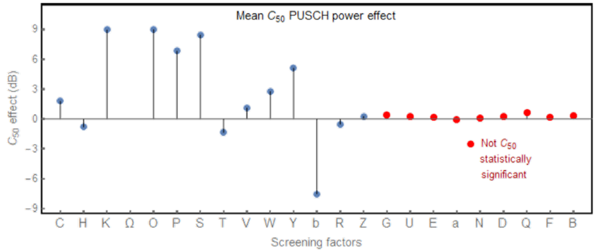
NIST



Inferential Analysis

- **Goal:** Identify statistically-significant effects on the PUSCH power per PRB distribution
- **Complications:**
  - Response variable is an empirical ***distribution***, not a scalar or a vector
  - PUSCH power per PRB distributions are frequently ***multimodal***

Median power effect – ANOVA of C_{50}

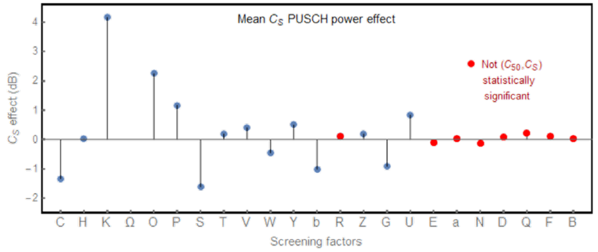


How to detect general changes in distribution shape? Percentiles!

Two step approaches:

1) Complex feature, simple inferential analysis method
   - Perform principle component analysis (PCA) on vector of all percentiles
   - Linear mapping from percentiles to vector of component scores
   - Perform univariate **ANOVA** on first principle component score to estimate significance of factor effects
2) Simple features, complex inferential analysis method
   - Use median, 95th percentile to describe each empirical distribution
   - Perform multivariate analysis of variance **(MANOVA)** to estimate significance of factor effects

Spread effect – MANOVA of (C_{50},C_S)



Key Findings

Largest factor screening experiment by NIST:

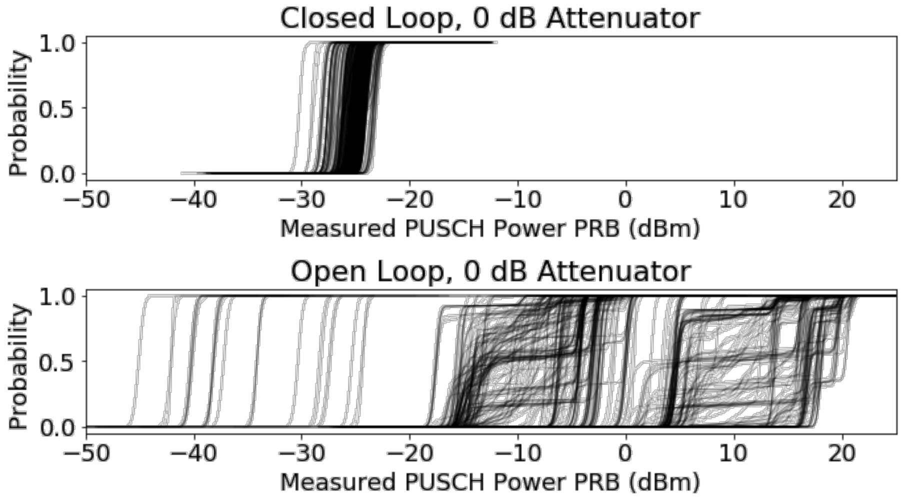
- 28 factors with 32 settings. Over 1,028 unique configurations tested (x4)
- > 900,000 data files validated

"Surprises" that could only be determined by statistical analysis.

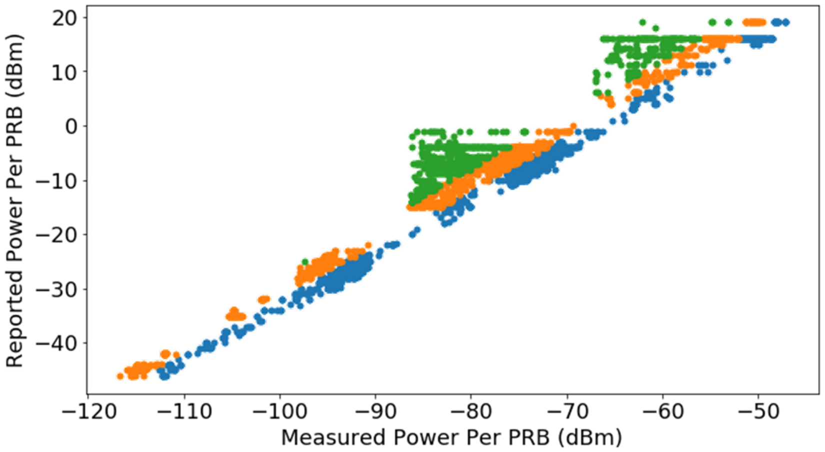
- Closed Loop power control had a significantly smaller distribution than open loop
  - → Use of this setting could enable improved modeling and reduce the safety factor in the interference equation
- Measured power was always equal or less than reported
- Several factors turned out to be significant that were not originally expected to be: (Ex: Target Upper Link Outer Scheduling, Scheduling Weight Uplink for SRS)

Challenges:

- **Automation was key to ensure sufficient data for rigorous uncertainty assessment and statistical analysis.**
  - Commercial equipment not intended for automation and frequent configuration changes.
  - Significant effort to optimize test matrix and stabilize test bed
- **Large numbers, and UE emissions as a distribution → statistical analysis**
  - Complexity required the team to develop new statistical procedures, and validate them

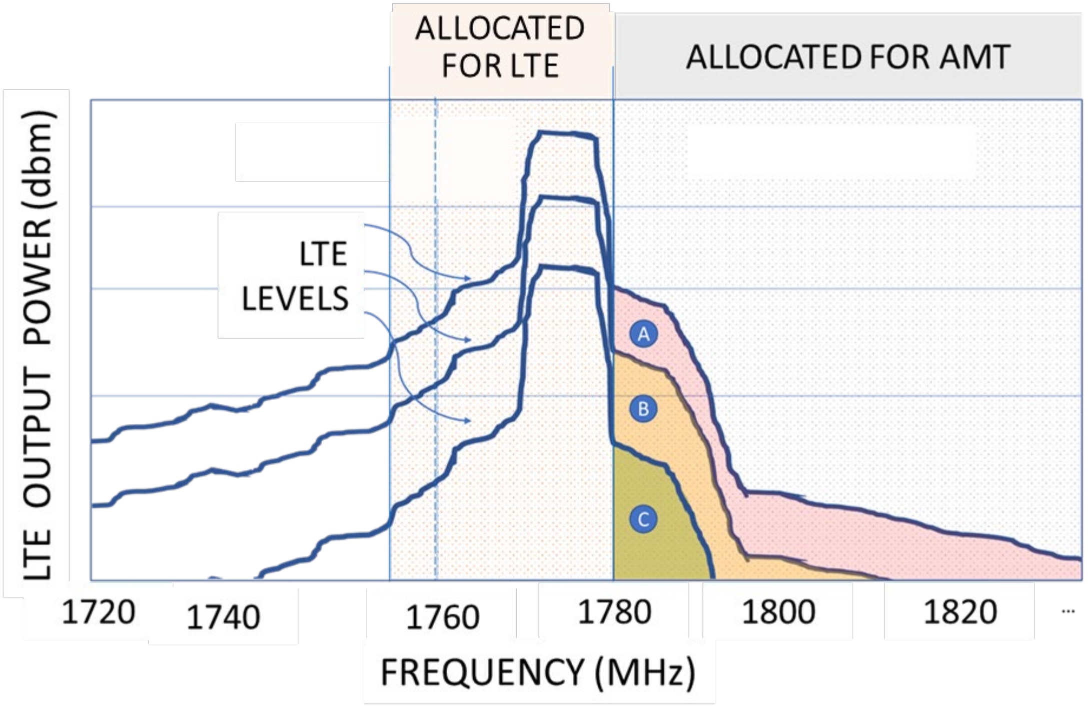


Measured vs Reported Power



AWS-3 LTE Impact on AMT
(Adjacent Band LTE)

NIST



AWS-3 auction led to compressed operations of DoD range Aeronautical Mobile Telemetry (AMT) systems.

AMT infrastructure remains unchanged, and current Inter Range Instrumentation Group (IRIG) Protocols for mitigating interference do not include new waveforms such as LTE.

Project will develop

- New coexistence metrics and compatible methodologies for multiple waveforms
- A curated set of LTE waveforms for future testing of multiple range environments.

LTE Impacts on AMT: Key Challenges

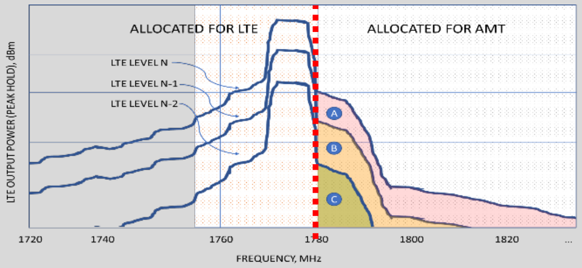
AMT Systems

- Previous operations in the "upper L-Band" **1755-1850 MHz,** limited spectrum neighbors.
- Traditional interference mitigation through scheduling
- **Compressed Operations: 1780 – 1850 MHz**

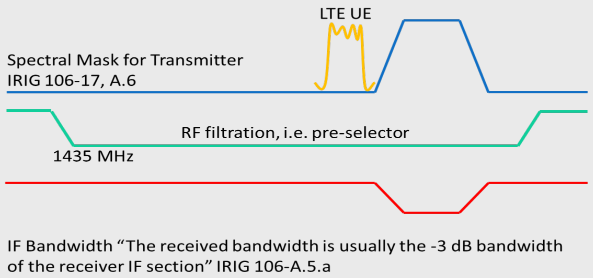
LTE (AWS-3)

- Adjacent to AMT's Compressed operations
- Downlink in 2110 – 2200 MHz
- **Uplink in 1755 – 1780 MHz**

NASCTN : <u>LTE Out-of-Band Emissions in the AWS-3 Band</u>



➢ Previous testing indicates the high energy levels of LTE adjacent to the AMT operating band have significant "roll off " shoulders well into the into the AMT that *could* impact the receiver.



- Broad RF filtration
- Narrowband and selectable IF filtering

➢ Although IF filtered, the wide band receiver still receives significant RF energy which could impact missions

TASK 1) Sensitivity and susceptibility analysis
Effects on AMT using a curated set of LTE waveforms of varying signaling conditions

TASK 2) Library of LTE waveforms
Captured from laboratory and in situ settings

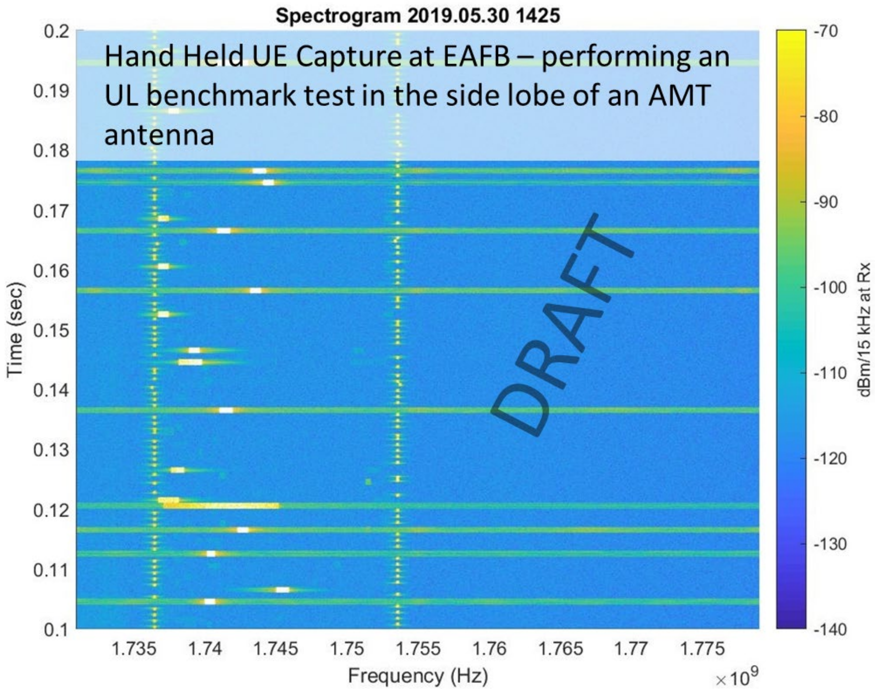
TASK 3) In-Situ captures
Using AMT infrastructure to inform scenario development for current and future testing
(Note: using deployed AWS-1 as a stand in for AWS-3)

Lab and In-Situ Measurements

Aggregate Emissions

Test conducted at Band 4 (AWS-1).

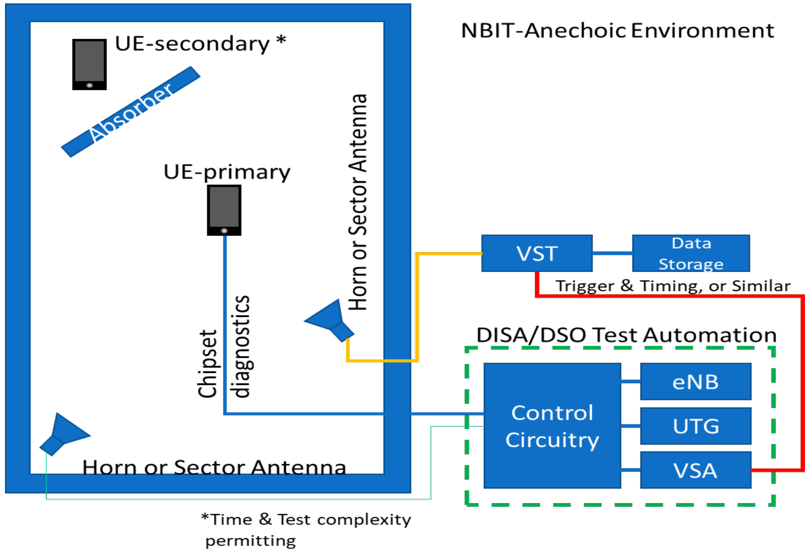
AWS-1 in-situ captures of Single UE and UEs in aggregate are stand-in for AWS-3



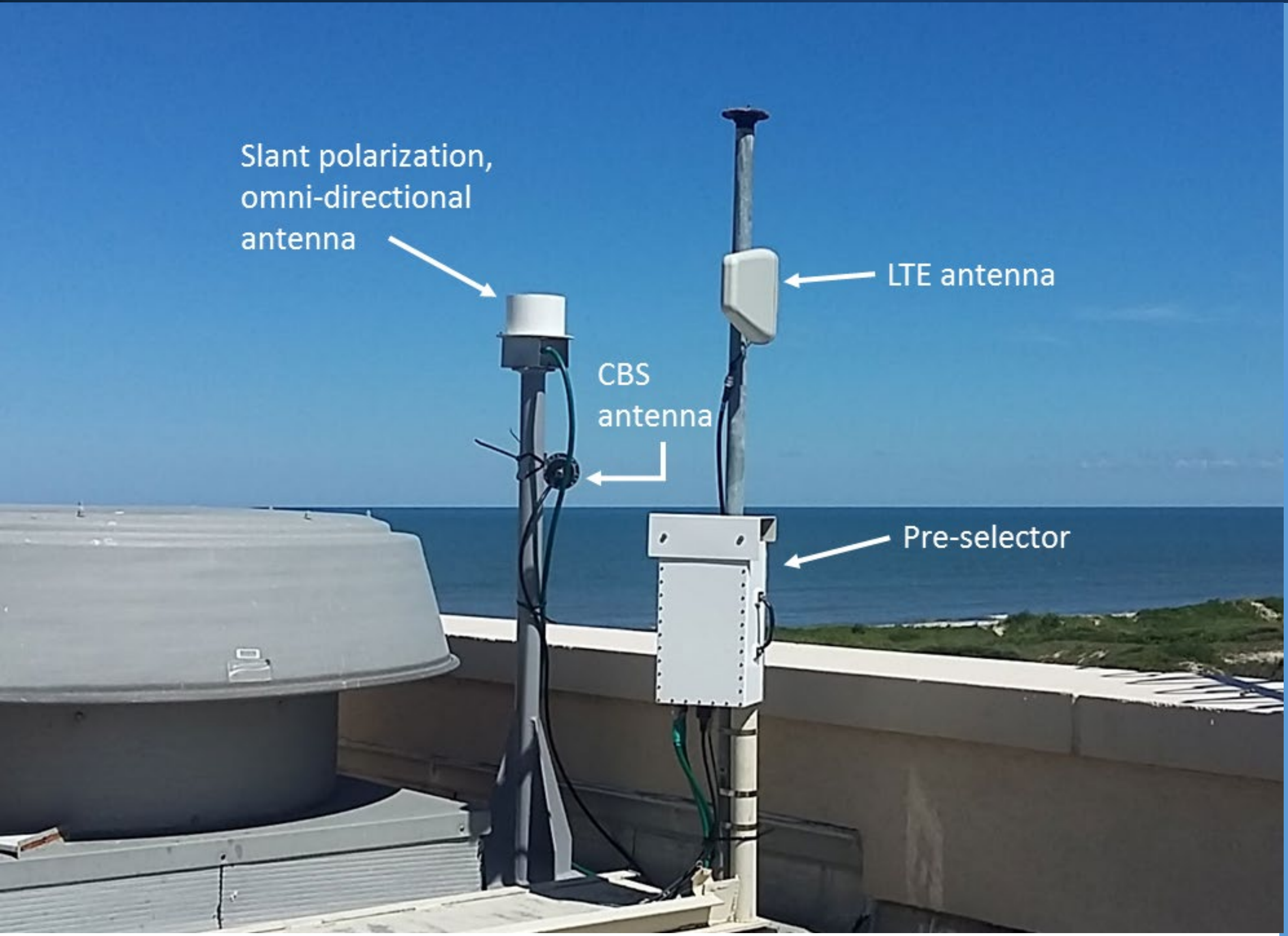
Single Emissions

Collection of captured live, radiated waveforms in high-fidelity to be replayed in later system testing.

Controlled lab setting, Band 66 (AWS-3) under varying network and UE traffic conditions *(background + UE itself)*



3.5 GHz Radar Waveform Measurements



Measurements are "For Official Use Only"

Objectives

- Characterize shipborne SPN-43 radar
- Create waveform library

Measurements collected

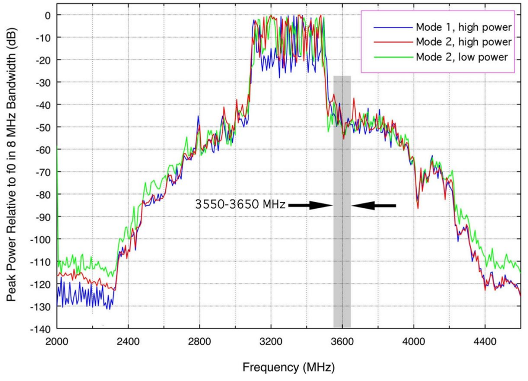
- Two naval bases: San Diego, Norfolk
- 2 months at each location

Outcomes

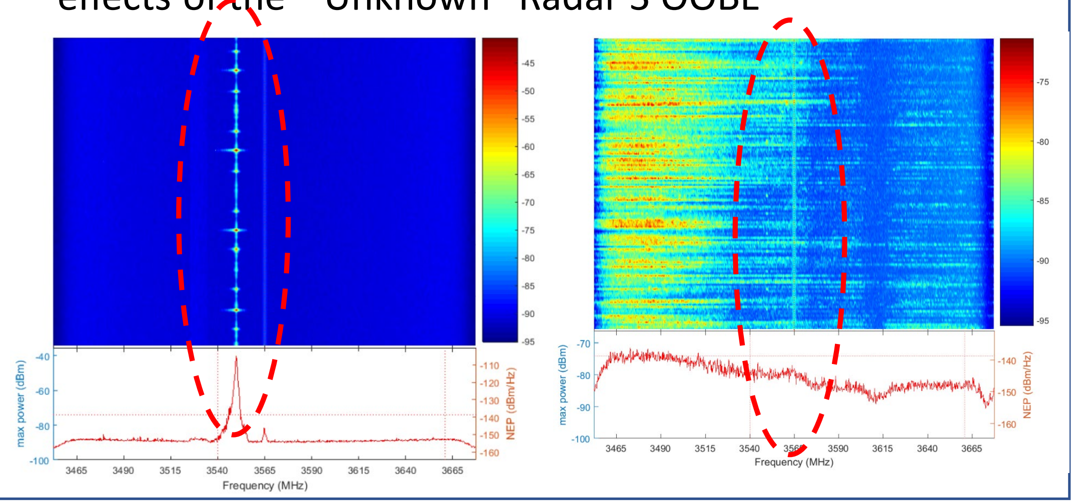
- 14,739 spectrograms, every 10 min
- 3,336 sixty-second IQ waveform captures (200 MHz inst. bandwidth)

3.5 GHz Radar Waveform Measurements: Results

"Unknown" Radar 3 system in adjacent band caused un-intentional emissions into the 3550-3650 Band

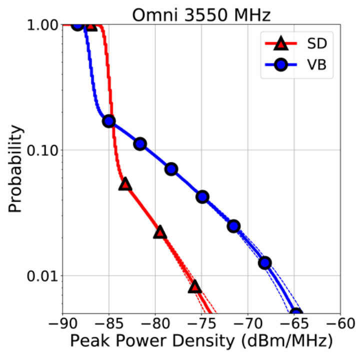


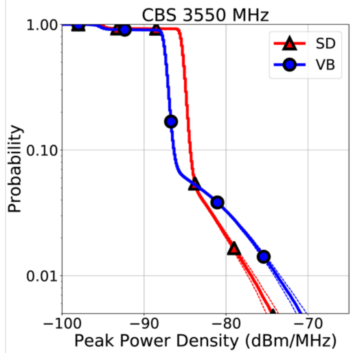
Example Spectrograms: Primary target SPN-43 and effects of the "Unknown" Radar 3 OOBE



13 algorithms tested, best in class:

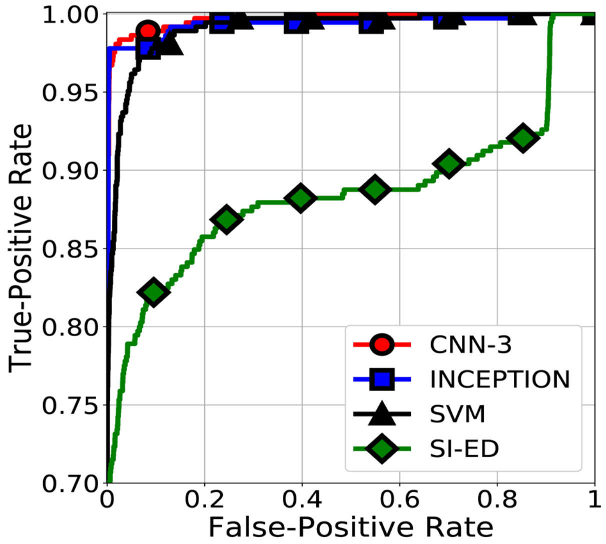
- Convolutional neural network with three layers (CNN-3)
- Inception, a deep neural network developed for computer vision
- Support vector machine (SVM)
- Energy detection correlated with radar antenna sweep period (SI-ED)





Antenna	Location	Count	Percentile	Estimate (dBm/MHz)
Omni	SD	3,455	50th	-85.2, [-85.2, -85.1]
			75th	-84.8, [-84.8, -84.7]
			90th	-84.3, [-84.3, -84.2]
			95th	-82.9, [-82.9, -82.8]
			99th	-76.4, [-76.7, -76.0]
	VB	1,788	50th	-87.0, [-87.0, -86.9]
			75th	-86.4, [-86.4, -86.3]
			90th	-80.8, [-80.8, -80.6]
			95th	-76.0, [-76.1, -75.8]
			99th	-67.2, [-67.7, -66.7]
CBS	SD	2,442	50th	-85.2, [-85.2, -85.1]
			75th	-84.8, [-84.8, -84.7]
			90th	-84.4, [-84.4, -84.3]
			95th	-83.6, [-83.6, -83.5]
			99th	-76.9, [-77.3, -76.5]
	VB	4,250	50th	-87.4, [-87.4, -87.2]
			75th	-86.9, [-86.9, -86.8]
			90th	-86.3, [-86.3, -86.2]
			95th	-83.3, [-83.4, -83.1]
			99th	-73.8, [-74.1, -73.4]

Significant proportion of non-SPN-43 emissions above -89 dBm/MHz



CNN-labelled spectrograms used to derive statistics of CBRS channel occupancy, vacancy, and noise-plus-interference levels

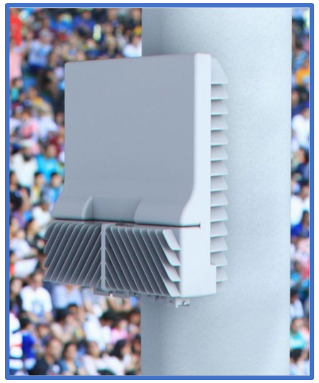
5G Spectrum Sharing Testbed (FR1, FR2)

NIST

Test Environment for Methods in Spectrum Sharing, Coexistence, & Interference Evaluation

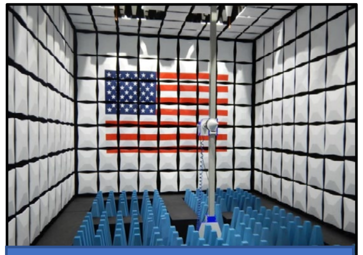
Complete Network Infrastructure

- Standalone IT network (with 5G virtual EPC)
- Carrier-grade base stations (eNB, gNB)
- Reconfigurable for specific scenarios
- Able to monitor network at any point: physical layer or IP.
- Diagnostic tools (4G/5G): Sanjole, QXDM,…

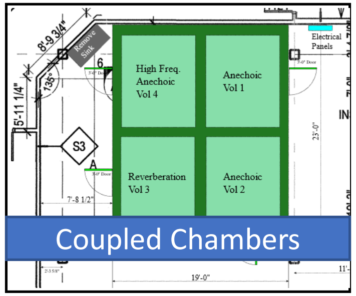


Physical RF Environments

Anechoic
Semi-Anechoic
Reverberation
Conducted
Hybrid



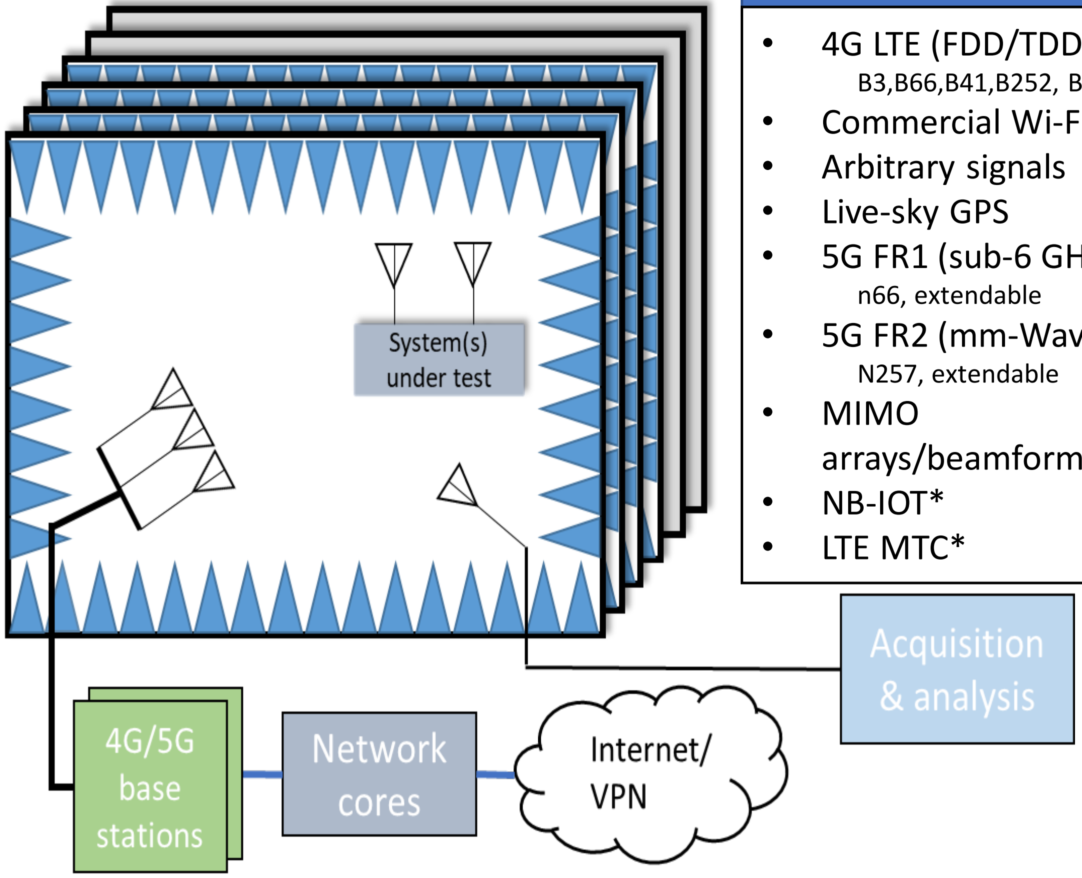
NBIT – 3m Anechoic



Coupled Chambers

Comprehensive Signal Analysis

- UE RAN emulation for network loading
- Metrics for Coexistence
- Metrology of spectrum sharing methods
- Waveform captures & playback
- In-band and Out-of-band Emissions
- Sensitivity and susceptibility analysis

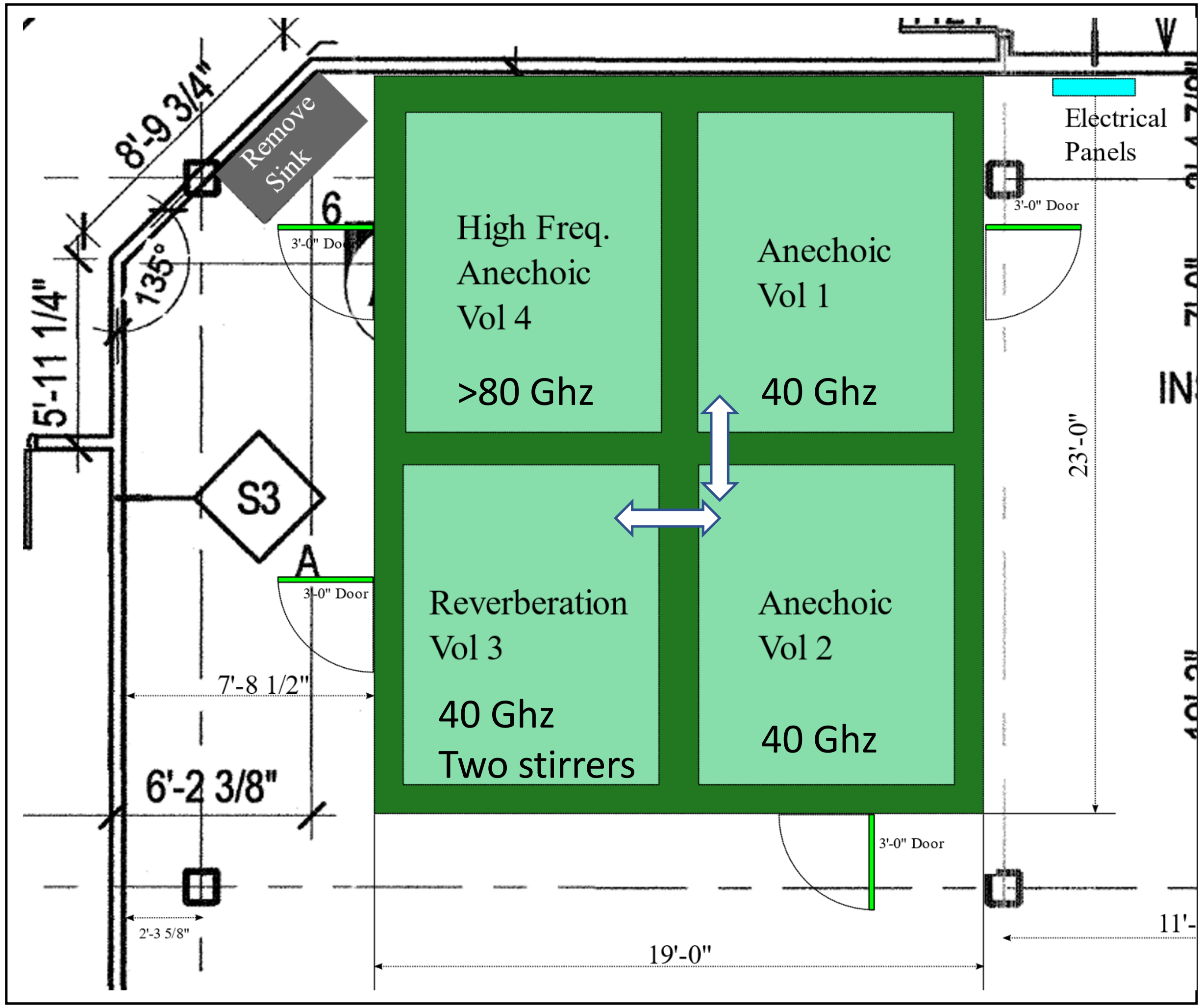


Deployed Capabilities

- 4G LTE (FDD/TDD/LAA)
  B3,B66,B41,B252, B255
- Commercial Wi-Fi
- Arbitrary signals
- Live-sky GPS
- 5G FR1 (sub-6 GHz)*
  n66, extendable
- 5G FR2 (mm-Wave)*
  N257, extendable
- MIMO arrays/beamforming*
- NB-IOT*
- LTE MTC*

*Installation Nov 2019, Nokia Airscale BBU/RRH

5G: Coupled Chambers



Vol 1 & 2: Anechoic

- Working Volume: 2.2 m x 2.8 m x 2.12 m
- Frequency: 0.5 – 40 GHz

Vol 3: Reverberation

- Working Volume: 2.7 m x 3.3 m x 2.8 m
- No. of Mode Stirrers: 2

Vol 4: Anechoic

- Working Volume: 2.4 m x 3.0 m x 2.3 m
- Frequency: up to 170 GHz

Other Features:

- Coupled: Vol 2 can be linked with Vol 1 and Vol 3
- Each room measures ~9'x11'
- 40 GHz anechoic chambers have ceiling mount capable of holding small robotic arm

5G Spectrum Sharing Testbed Roadmap

NIST

Implement, characterize, and apply an end-to-end 5G mm-Wave LTE network for spectrum sharing & wireless coexistence challenges

Operating Modes:

- Non-standalone: 4G uplink, 5G downlink (FY20)
- Standalone: 5G uplink and downlink (FY21)
- Coupled chambers: 3 anechoic & 1 reverb (FY20)
- Hybrid (radiated & Conducted) testing of 5G architecture (FY20)

FY20 Testbed V&V Goals:

- Baseline radiated, network, and 5G hardware performance
- RF circuitry design for hybrid testing. *Ex: Dynamic, controllable RF link (focus on pathloss) for testbed.*
- Leverage existing 4G code framework for automated testing, data acq.
- Establish RF measurement uncertainty characteristics of the testbed

FY20 research:

- (Funded) Investigate subset of factors within 5G that control radiative behavior.
  - Leverage (DISA/DSO project) 4G factor screening understanding to investigate 5G architectures that determine the radiative behavior of user equipment
- (Funded) New metrology tools for Communications systems testing in highly-reflective environments.
  - Revise methods/guidance on use of reverb chambers for communications systems (eNBs). Statistical methods not adapted from EMC CW yet.
  - Measurement tool based on software defined radios (SDRs) that enables the in-depth study of reverberation chambers and their applications in wireless device testing. Example: testing MIMO systems
- (Potential) Investigation of impacts of proposed 5G service in the 24 GHz band

Summary

NASCTN supports the growing need for accurate, reliable, and unbiased measurements and analyses to support increased spectrum sharing by both federal agencies and non-federal spectrum users.

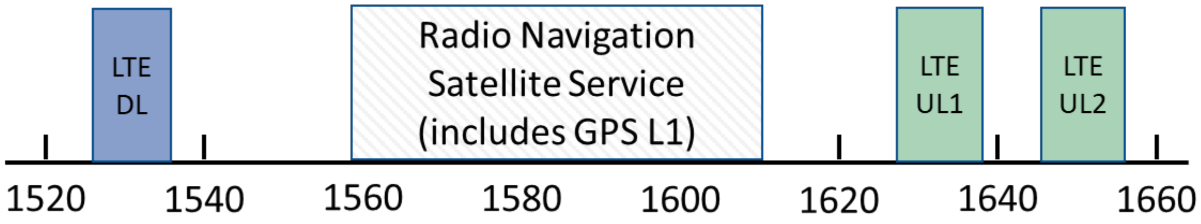
NASCTN projects follow an open, transparent and comprehensive process for developing *independent*, scientifically based test plans, facilitating access to member test ranges and laboratories, protecting controlled information, and validating test results before findings are reported.

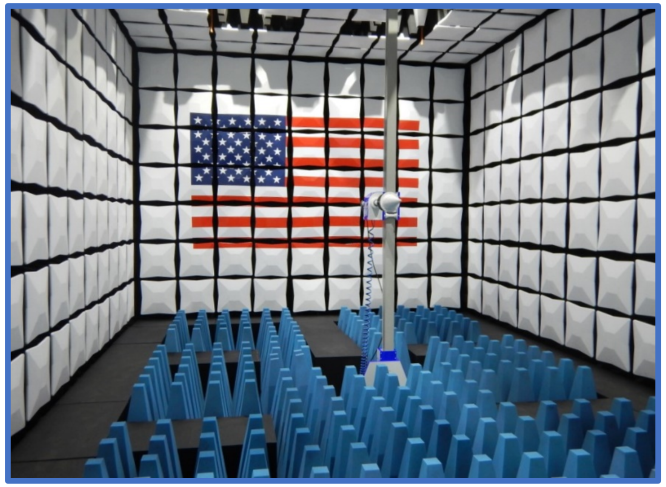
Advances in **metrology** for spectrum sharing (ie. In-Band and Out-of-Band emission impacts; Factor Screening; expanded inferential statistical analysis; formal Design of experiment) has led to the ability to characterize communication systems that often have varied and distributed of responses.

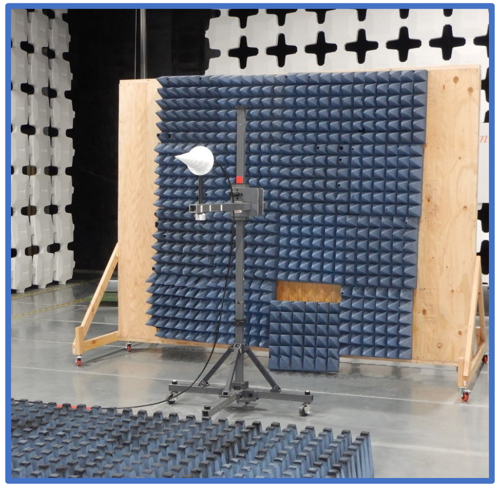
The **5G Shared Spectrum Testbed** will derive techniques and metrology with applications in everyday wireless communications, IoT, and 5G networks –furthering the NIST mission of promoting industrial competitiveness through advancing measurement science in telecommunications.

QUESTIONS?

LTE Impacts on GPS L1
(Adjacent Band LTE)







2011 - FCC grants conditional waiver to Ligado to deploy terrestrial LTE network adjacent to GPS L1 band

FCC suspends waiver due to potential interference. Extremely controversial, misinformation (multiple measurements).

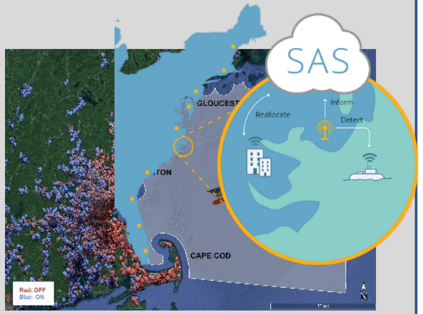
A trusted neutral party was required to investigate and measure effects of LTE signals on GPS receivers → NASCTN founded

Provided independent test methodology and data directly to regulators and stakeholder community.

2017 DoC Gold Metal

NIST's Efforts Related to Trusted Spectrum Testing

NASCTN



CBRS and SAS

Core Challenges

Coexistence Metrics	Coexistence metrics and testing methods for wireless systems in shared-spectrum environments
Spectrum Management	Impartial trusted source for test methods to evaluate effectiveness of centralized spectrum-management approaches
Waveform Metrology & Calibration	Traceable and rigorous test methods for OTA testing of wireless systems. Quantify RF environments, spectrum usage and wireless system behavior

Over the Air (OTA) Testing

CBRS WInnForum Standards™

Standards Development

Targeting Future Challenges

Develop Metrology and Curated data sets

- ML Training and evaluation
- RF interference and sensing testing ("impact")
- 5G, Optical networks

Machine Learning / AI

Pro-Active Measurements

- Key measurements in advance of spectrum auctions
- Early identification of issues and risks
- Improve investments

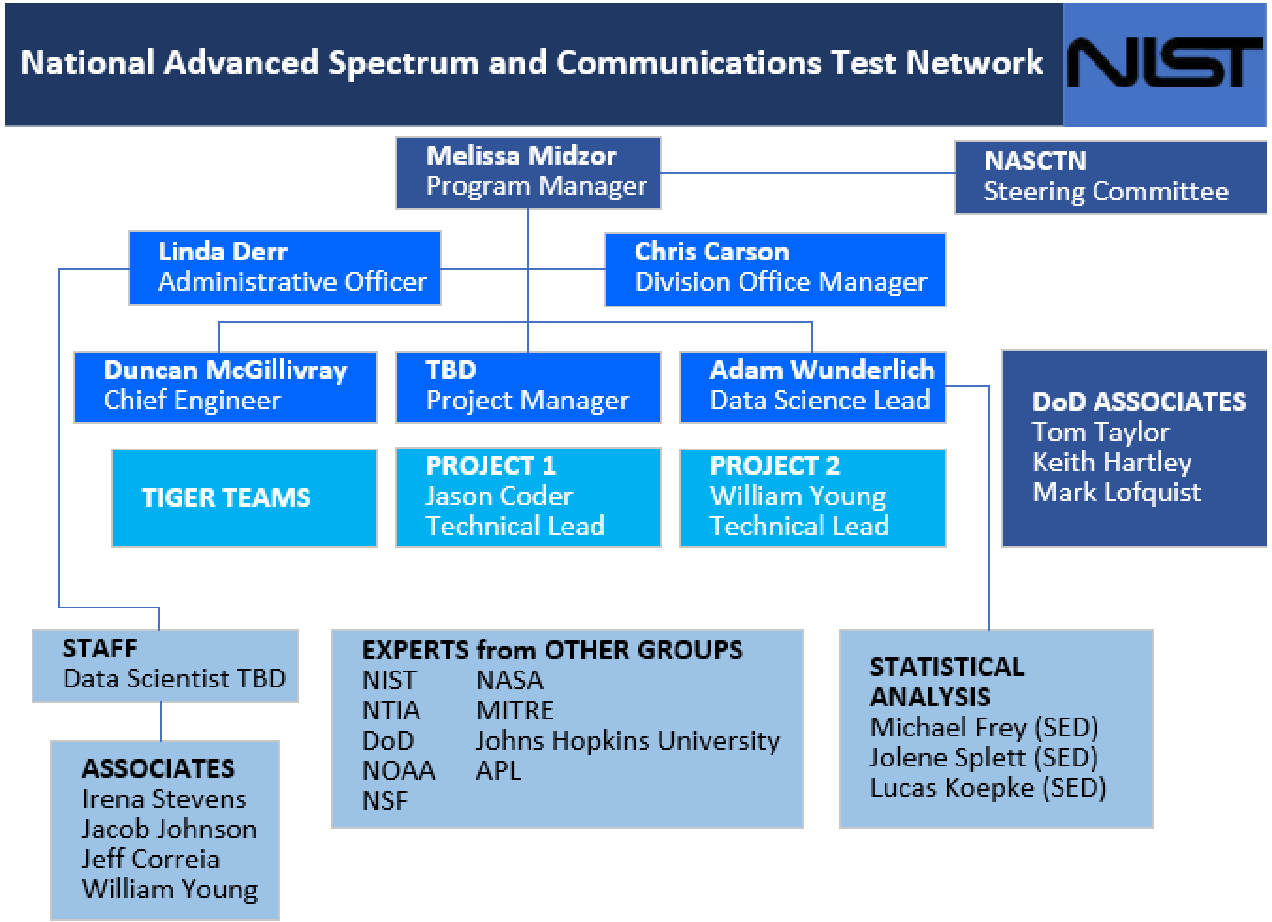
Future Auctions

Developing new Statistical Analysis

- Large # variables, complex interactions, distributed responses
- LTE, 5G and beyond, DoD mission testing

Data Science

Unique structure for flexible, adaptable teams

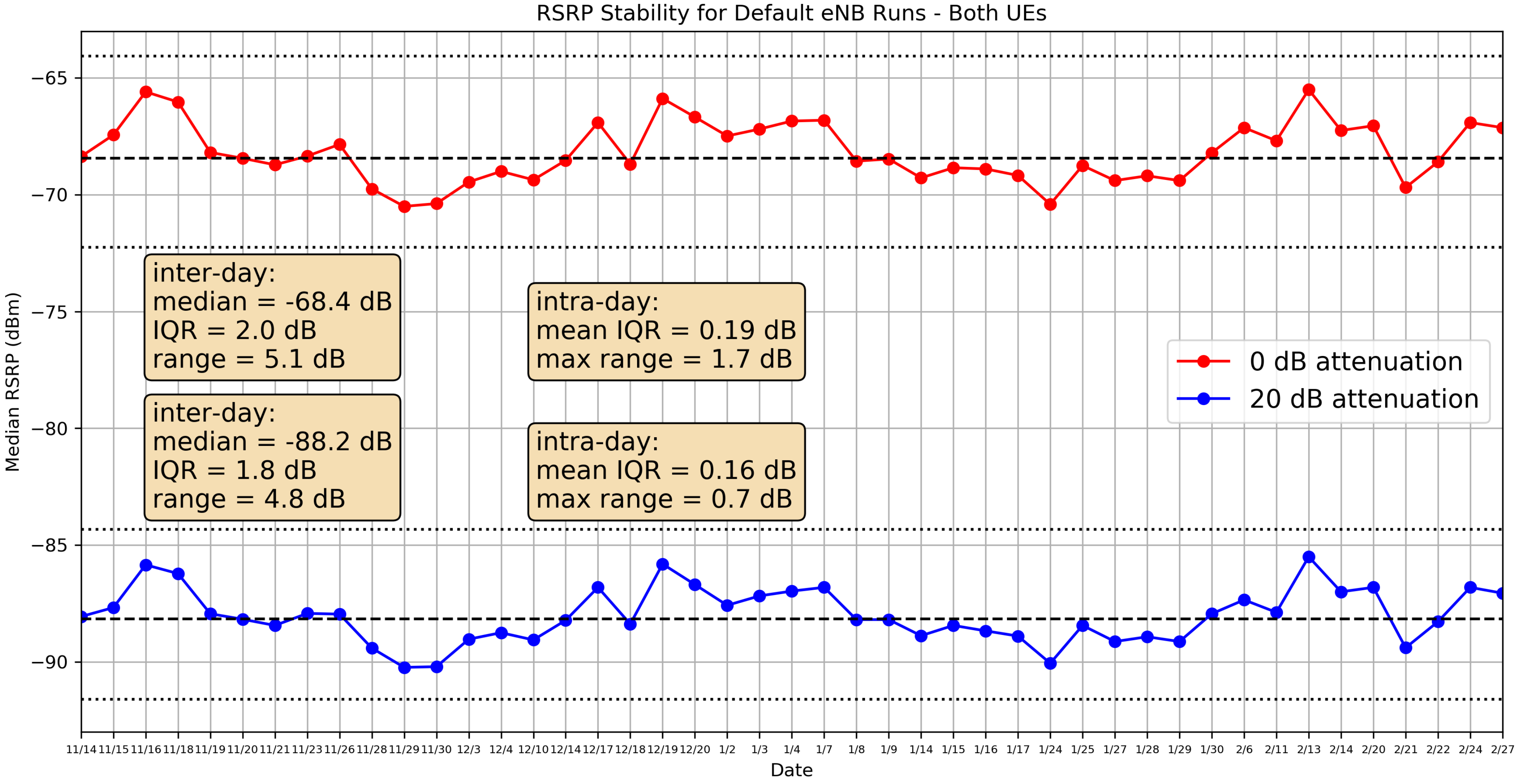


Core Group (Hosted at NIST)
Overall programmatic direction and coordination across partners, ensures technical quality, enables rapid start up

Subject Matter Experts (NIST, Other)
Each project employs personnel based on test requirements from NIST, NASCTN members, FFRDCs, CCS

Steering Committee
Provides guidance, outreach, approval of projects, and governance for NASCTN activities.

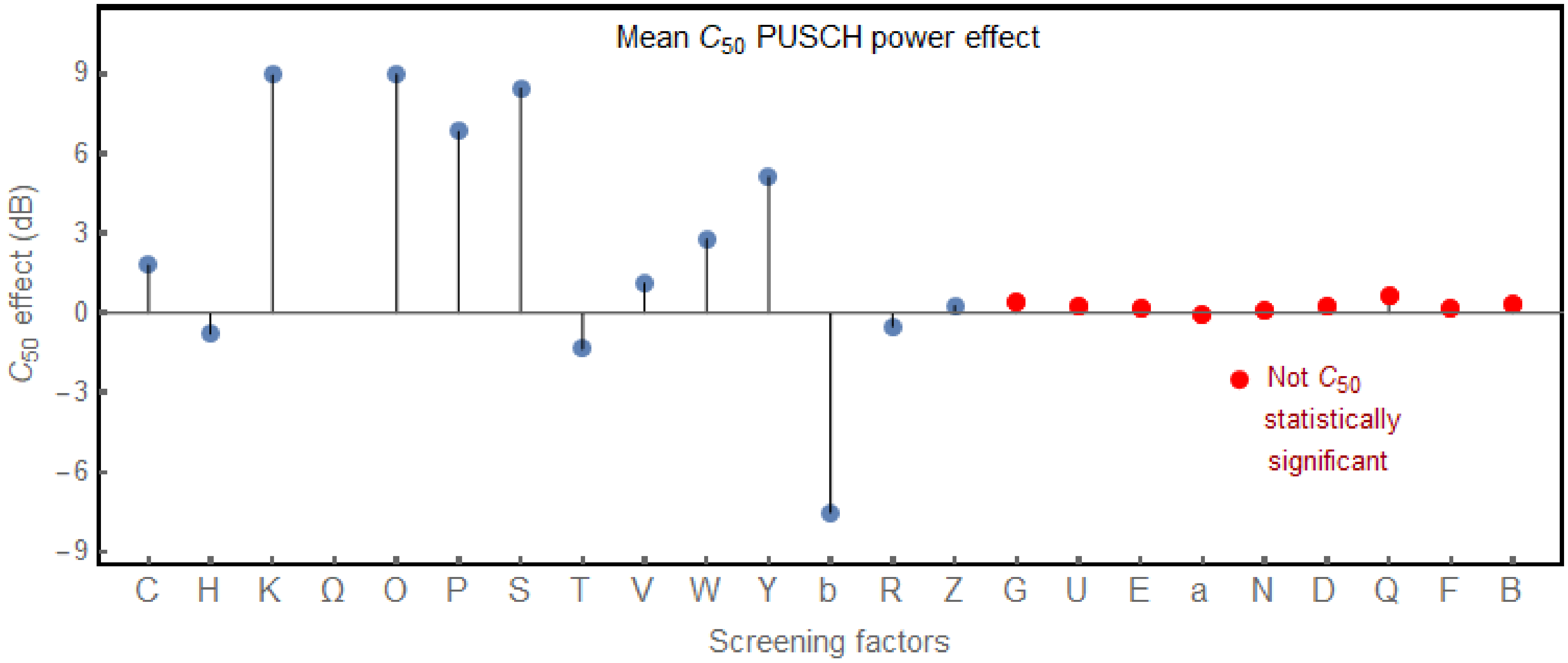
Aggregate AWS-3 LTE Emissions: Stability



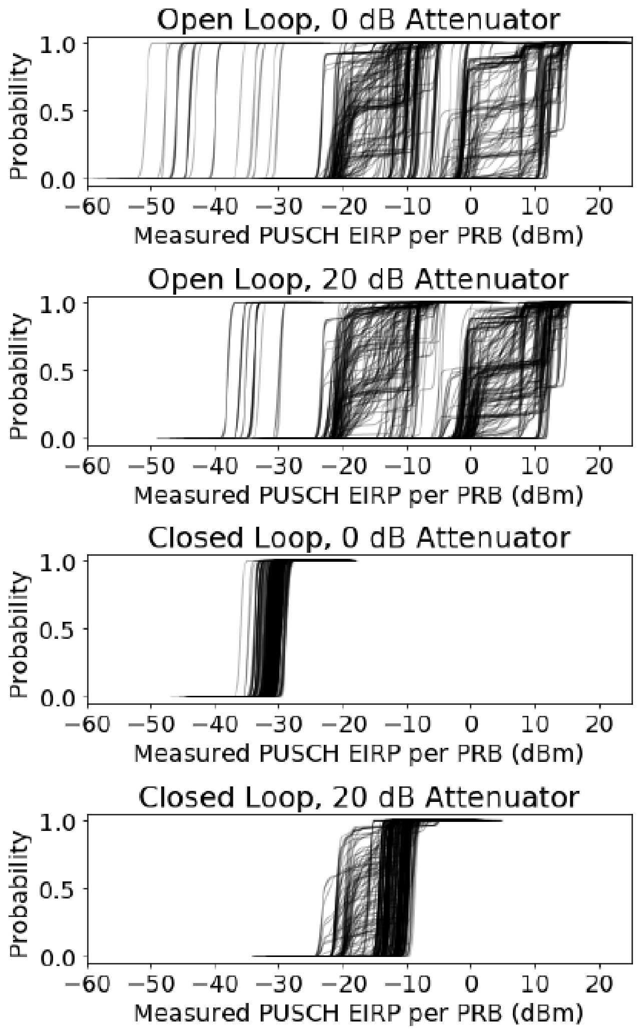
Aggregate AWS-3 LTE Emissions: Results

NIST

Median power effect – ANOVA of C_{50}



Aggregate AWS-3 LTE Emissions: Open vs Closed



Closed loop has tighter grouping, and varies as expected to path loss (attenuator settings)

If the carriers use this setting, could enable improved modeling and reduction of the safety factor in the interference equation (ie. more "green lights" for deployment)