AWS-3 LTE Impacts on AMT: Public Outreach Brief

May 12, 2021

NASCTN
National Advanced Spectrum and Communications Test Network

Audience Instructions

- Please Mute all connections
- Submit Questions in the Chat
  - Questions will be addressed after all major components
- To be called upon by the moderator please raise hand

Welcome

Context & Background

Technical Components

- Task 1: In-Situ Captures of AWS-1 LTE for Aeronautical Mobile Telemetry System Evaluation

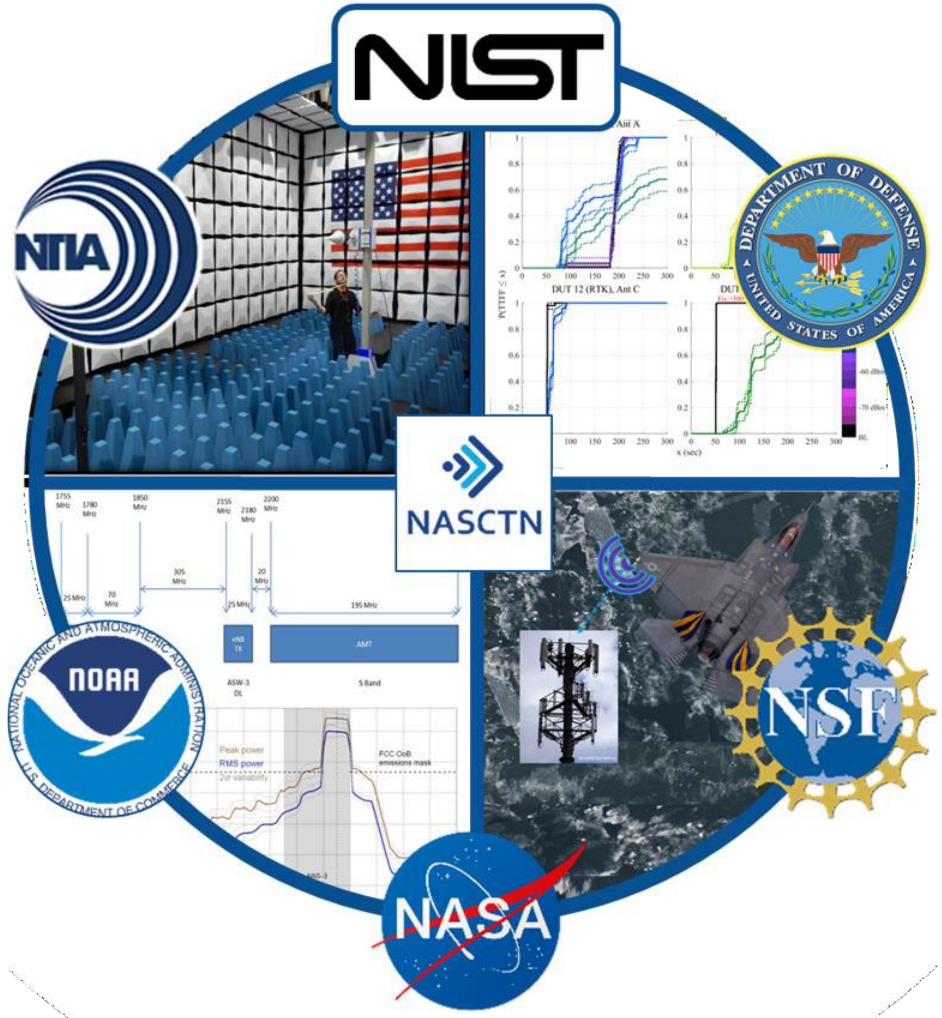
  Speaker: Eric Nelson, NTIA
- Task 2: Laboratory Methods for Recording AWS-3 LTE Waveforms

  Speaker: Duncan McGillivray, NIST
- Task 3: AWS-3 LTE Impacts on Aeronautical Mobile Telemetry

  Speakers: W.F. Young, MITRE; Duncan McGillivray, NIST; Adam Wunderlich, NIST

Wrap-up

National Advanced Spectrum and Communications Test Network (NASCTN)



- 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

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

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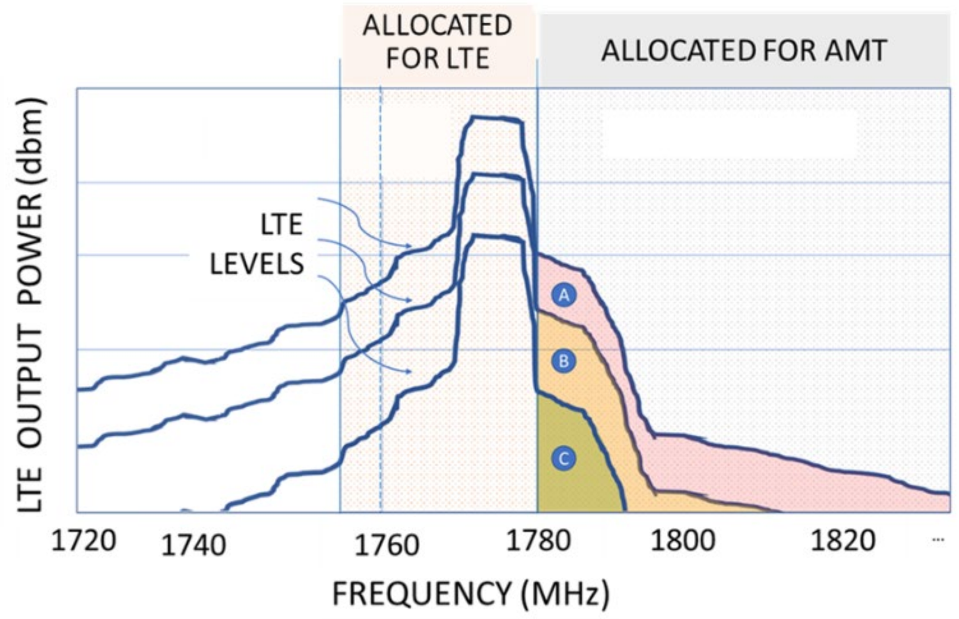
Acronyms Slide

- **ABE** – adjacent band emission
- **AMT** – aeronautical mobile telemetry
- **ARTM-CPM** – Advanced Range Telemetry continuous phase modulation
- **AWGN** – additive white Gaussian noise
- **AWS-1** – advanced wireless services – 1
- **AWS-3** – advanced wireless services – 3
- **Az** – azimuth
- **BER** – bit error rate
- **BW** – bandwidth
- **dBFS** – decibel relative to Full Scale
- **DUT** – device under test
- **EAFB** – Edwards Air Force Base
- E_b/N_0 - energy per bit per noise density
- **IRIG** – Inter-Range Instrumentation Group
- **LaRC** – Langley Research Center
- **LDPC** – low density parity check
- **LTE** – long term evolution
- **NASA** – National Aeronautics and Space Administration
- **NASCTN** – National Advanced Spectrum and Communications Test Network
- N_a^{eff} - effective ambient noise
- N_0 – noise spectral density
- **NIST** – National Institute of Standards and Technology
- **OBW** – occupied bandwidth
- **OOBE** – out of band emission
- **PL** - pathloss
- **PCM/FM** – pulse code modulation / frequency modulation
- **QPSK** – quadrature-phase shift keying
- **RB** – resource block
- **Rx** – receive
- S_{ave} – signal average power
- **SABE** – AMT Signal to ABE Power ratio
- **SOQPSK** – shaped offset QPSK
- **SOQPSK-FEC** – SOQPSK with forward error correction
- **STC** – space time coding
- **STC-FEC** – STC with forward error correction
- **Tx** – transmit
- **UE** – user equipment
- **UL** – uplink
- **VSA** – vector signal analyzer
- **VSG** – vector signal generator
- **WF** – waveform

AWS-3: Adjacent Band LTE to AMT

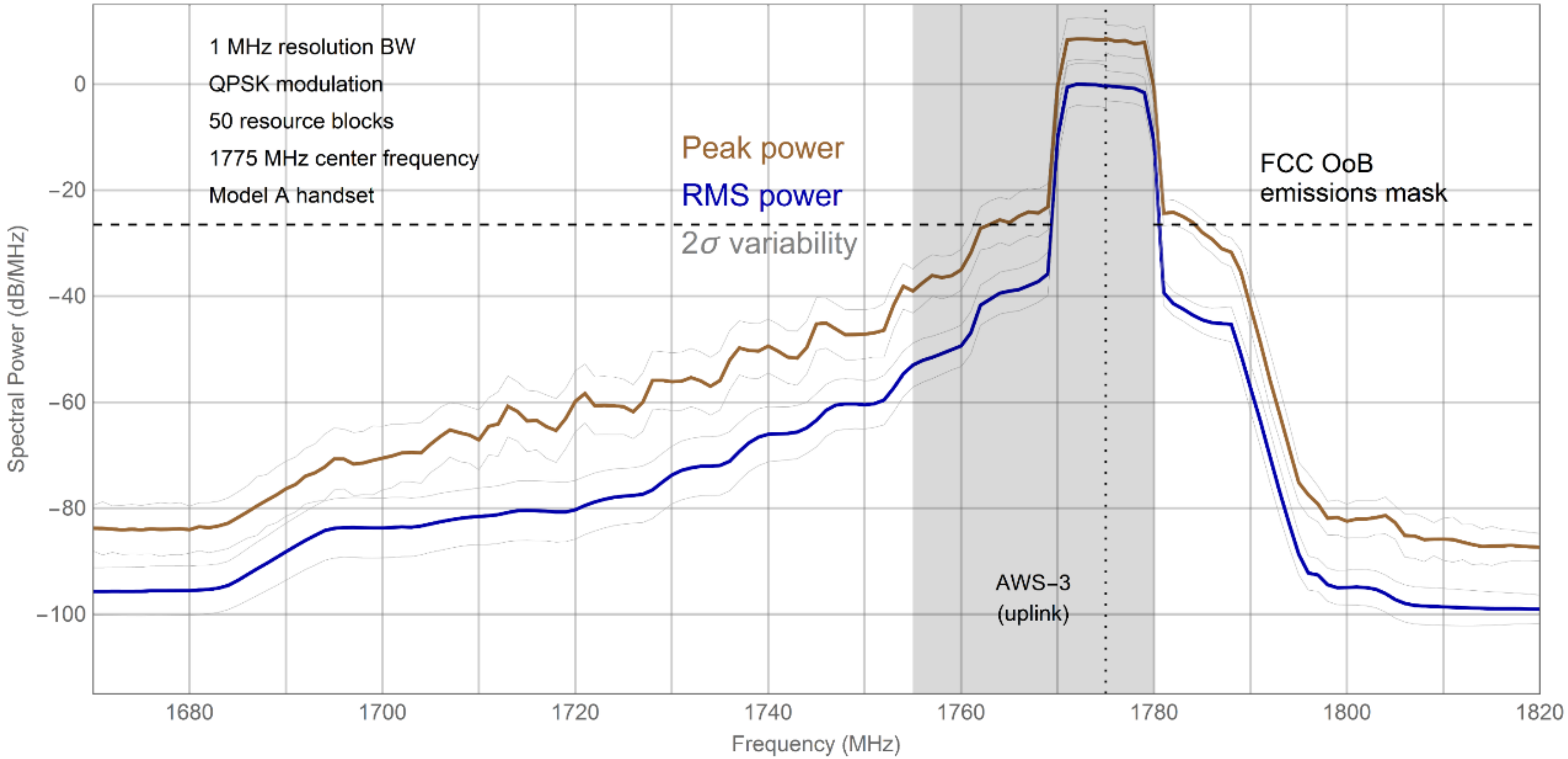


- AWS-3 auction led to compressed operations of DoD range Aeronautical Mobile Telemetry (AMT) systems.
- AMT infrastructure remains unchanged, and current IRIG protocols for mitigating interference do not include new waveforms such as LTE.
- NASCTN Projects focused on:
  - Out-of-band emissions measurements for LTE devices operating in the AWS-3 Band (2018)
  - Coexistence metrics and compatible evaluation methodologies for studying LTE impacts on AMT receivers (2021)
  - Developing a curated set of LTE waveforms for future testing of multiple range environments
    - Single and multi-user, uplink only (2021)

Prior NASCTN Project: Out-of-Band Emissions Measurements of LTE Devices Operating in the AWS-3 Band

- Report jointly published by NTIA and NIST Jan 2018:
  - NTIA TR-18-528, NIST TN-1980

Report presents power spectral densities of AWS-3 LTE OOBE with the potential to impact operation of physically co-located AMT systems in adjacent bands.



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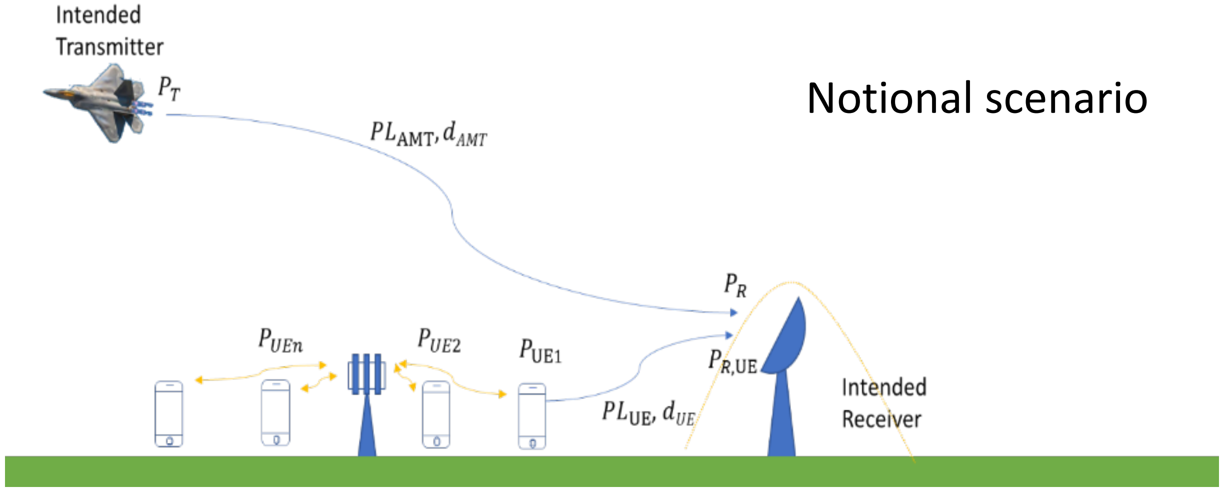
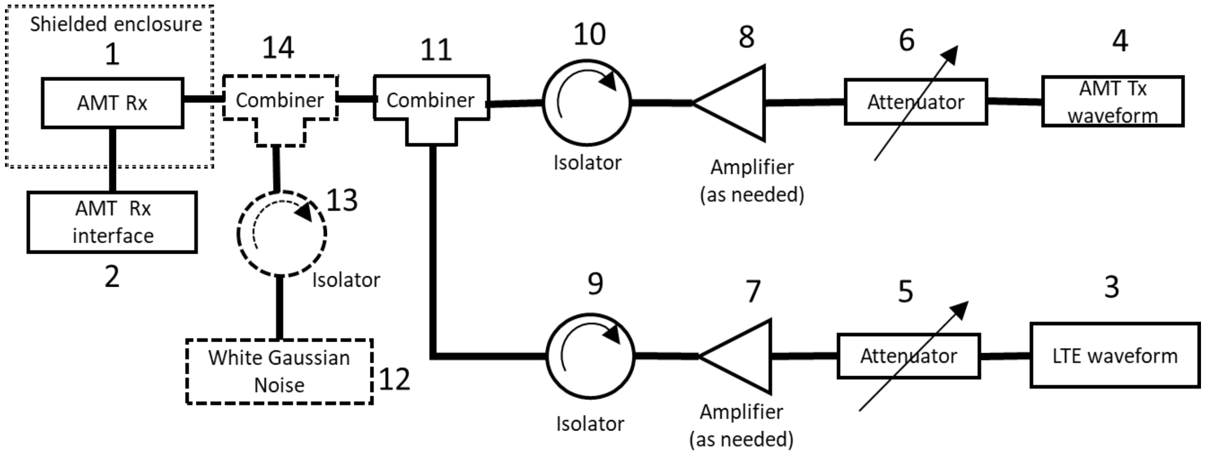
Test Plan Review

Susceptibility Study Test Plan Concept





- **Collect radiated LTE uplink waveforms in-situ and in-laboratory**
  - Surrogate in-situ LTE form translated to AWS-3 band
  - In-situ waveforms captured through telemetry receiver antennas and at the input to the AMT receiver
- **Collect multiple Key Performance Indicators**
  - Bit error rate, signal-to-noise ratio, E_b/N_0, etc.
  - Include Gaussian noise waveforms
- **Process and analyze data**
  - Compare against IRIG band edge back off recommendations
  - Investigate relation of impacts to "equivalent in-band Gaussian noise"
- **Two Laboratory Testbeds**
  - NIST/NASCTN Boulder, CO
  - MITRE Bedford, MA

Test Outline

	Overview of testing efforts	Resources
1	**Collect In-Situ LTE waveforms/spectrograms at AWS-1** a. Capture LTE signals in a variety of AMT environments (EAFB, NASA Langley) b. Informs efforts #1 and #2 on network laydown and settings c. Use waveforms/spectrograms to playback/build interference waveforms for effort #1 & future tests	NTIA, NIST, NASA, EAFB 
2	**Generate Waveforms (and Library for future testing) - Radiated Tests In Lab** a. Leverage existing equipment and test benches to generate and capture LTE – UL waveforms b. Develop & measure various radiated test scenarios c. Establish a "Library of LTE – UL waveforms" that can be leveraged for this and & future tests	NIST 
3	**Sensitivity and Susceptibility Testing - Connectorized Lab bench test with AMT hardware** **a.** **Test sensitivity** to various VSG produced signals. Unidirectional Tx -> Rx AMT link, using predefined data-payload/streams. **b.** **Test susceptibility** to generated LTE waveforms based on efforts #2, #3 i. Gain insights into response & relaxation time ii. Automate / execute tests in laboratory environment iii. Define, track, and analyze AMT Key Performance Indicators iv. Develop statistics required (output resultant distributions with uncertainties)	NIST, MITRE 

Task 1
In-Situ Captures of AWS-1 LTE for Aeronautical Mobile Telemetry System Evaluation

Presented by:

Eric Nelson, NTIA ITS

NASCTN
National Advanced Spectrum and Communications Test Network

In-Situ Captures of AWS-1 LTE for Aeronautical Mobile Telemetry System Evaluation

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12 May 2021

Background

- Measurement support to NASCTN leveraged ITS experience measuring LTE UE uplink aggregate transmissions for DISA/DSO's Spectrum Sharing Test and Demonstration (SST&D) program
- Carrier Coordinated Testing events have been ongoing since October 2018 in Longmont, Boulder, Denver and Grand Jct, CO as well as the SEC Football Championship game in Atlanta, GA
- Measurements of a wireless carrier's aggregate uplink transmission in the AWS-1 band (1710-1755 MHz) have served as proxies for future loading of the AWS-3 band (1755-1780 MHz)
- Given the carrier's cell laydown, the measurement data permit system modelers to compare measured aggregate power at the receive location to model predictions
- In-Situ Captures of AWS-1 LTE for Aeronautical Mobile Telemetry System Evaluation provided a unique opportunity to examine UE emissions *through a victim receiver*

Tech Tip: Align to LTE Uplink Modulation

- Center frequency between two subcarriers
- FFTs sized to band of interest
- FFT bins are 15 kHz and centered on LTE subcarriers

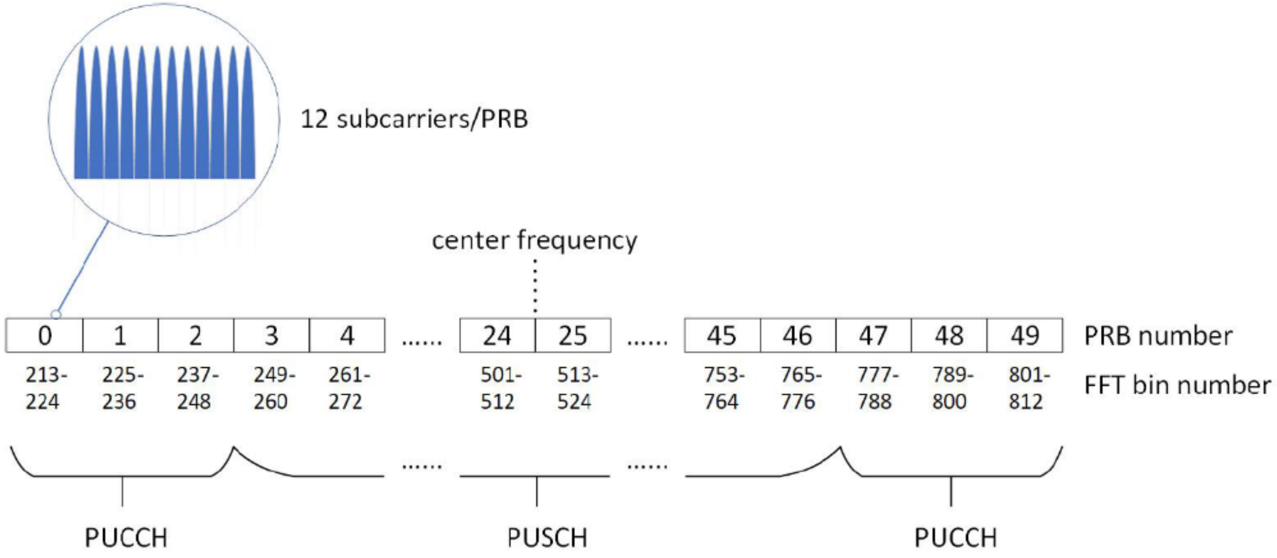


Figure 6. PRB and FFT bin identification for 10 MHz band.

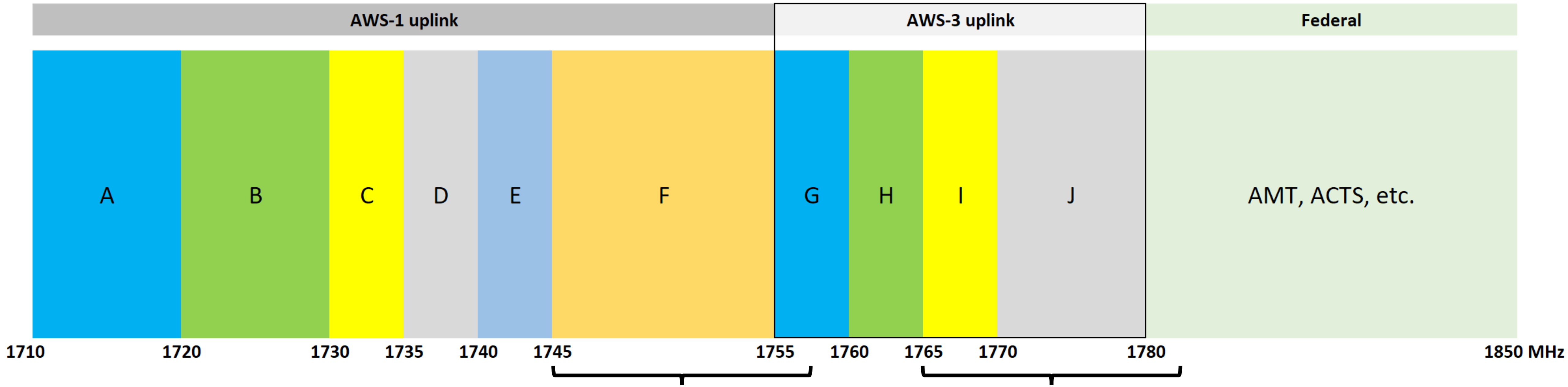
Key LTE uplink physical layer parameters [6] are as follows.

Table 3. LTE Uplink Physical Layer Parameters

Channel Bandwidth (MHz)	**5.0**	**10.0**	**15.0**	**20.0**
Occupied Bandwidth (MHz)	4.5	9.0	12.0	18.0
Number of PRBs	25	50	75	100
Sampling Frequency (MHz)	7.68	15.36	23.04	30.72
FFT size	512	1024	1536	2048
Sub-carrier spacing (kHz)	15			
VSA Span (MHz)	6	12	18	24

Reference NTIA Tech Memo 21-552 for more details

AWS Band Plans (uplink only)



LTE deployments in AWS-1 are mature but those in AWS-3 are not…

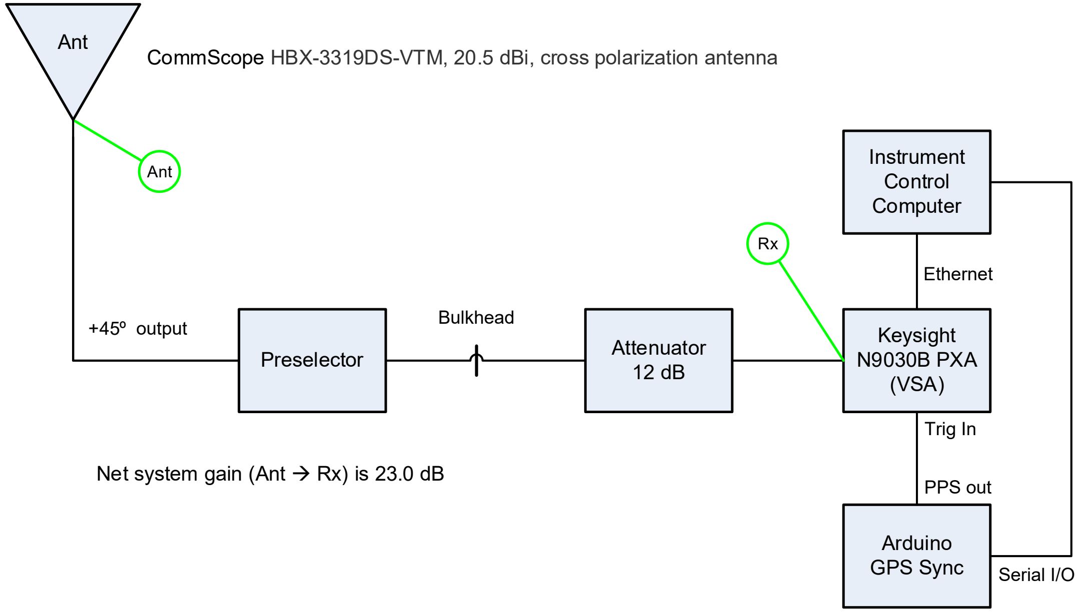
…so evaluate emissions here…

… as a proxy for emissions here…

… to assess impacts on Federal systems

Note: wireless carriers often combine adjacent licenses to permit larger LTE band deployments

Standalone VSA Capture System

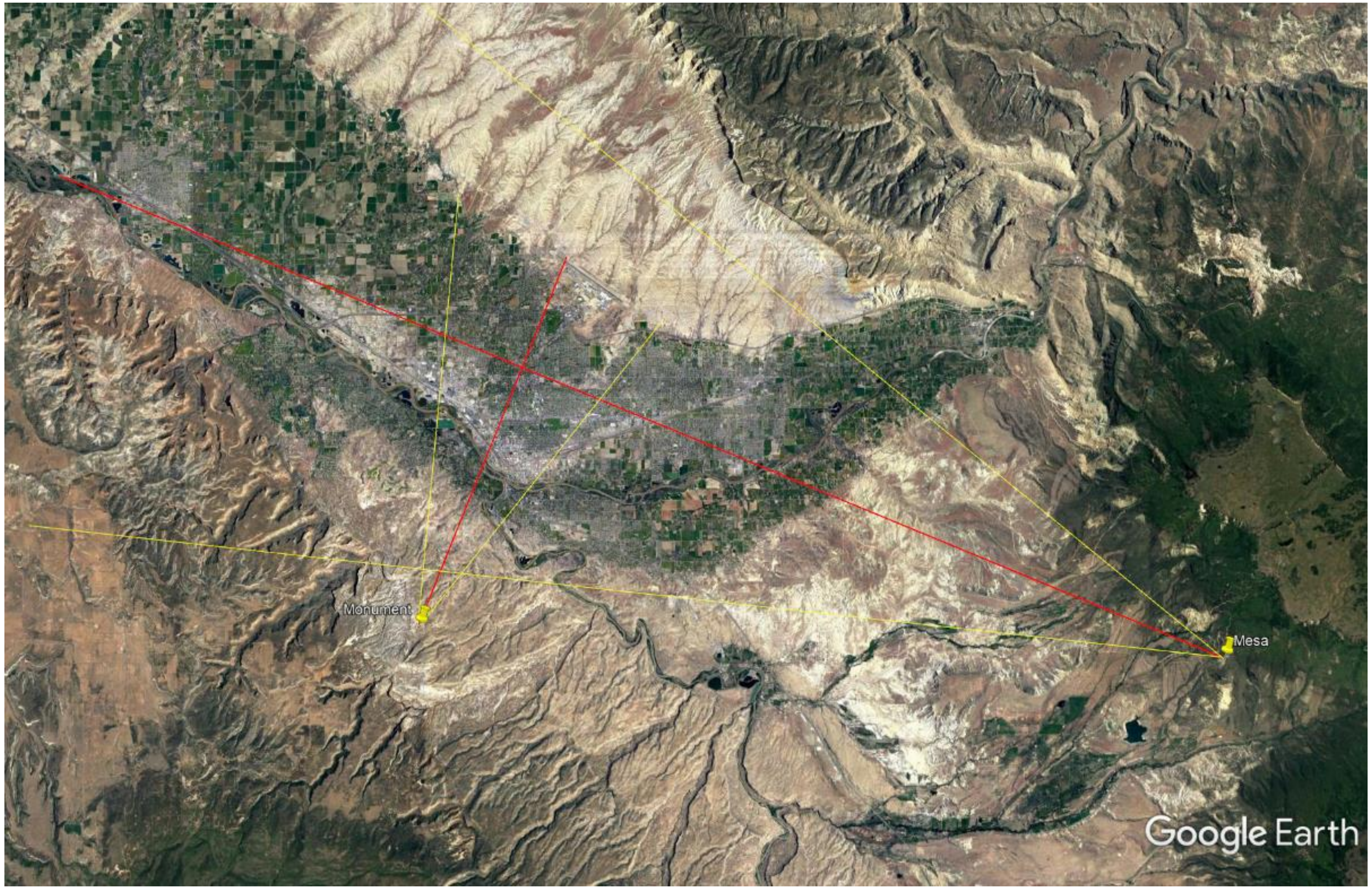


Aggregate UE emissions system deployed at Grand Mesa overlooking Grand Jct, CO

Standalone system was optimized for assessing aggregate interference from population centers. Measurements are referenced to the antenna terminal and impact on victim receivers is inferred.

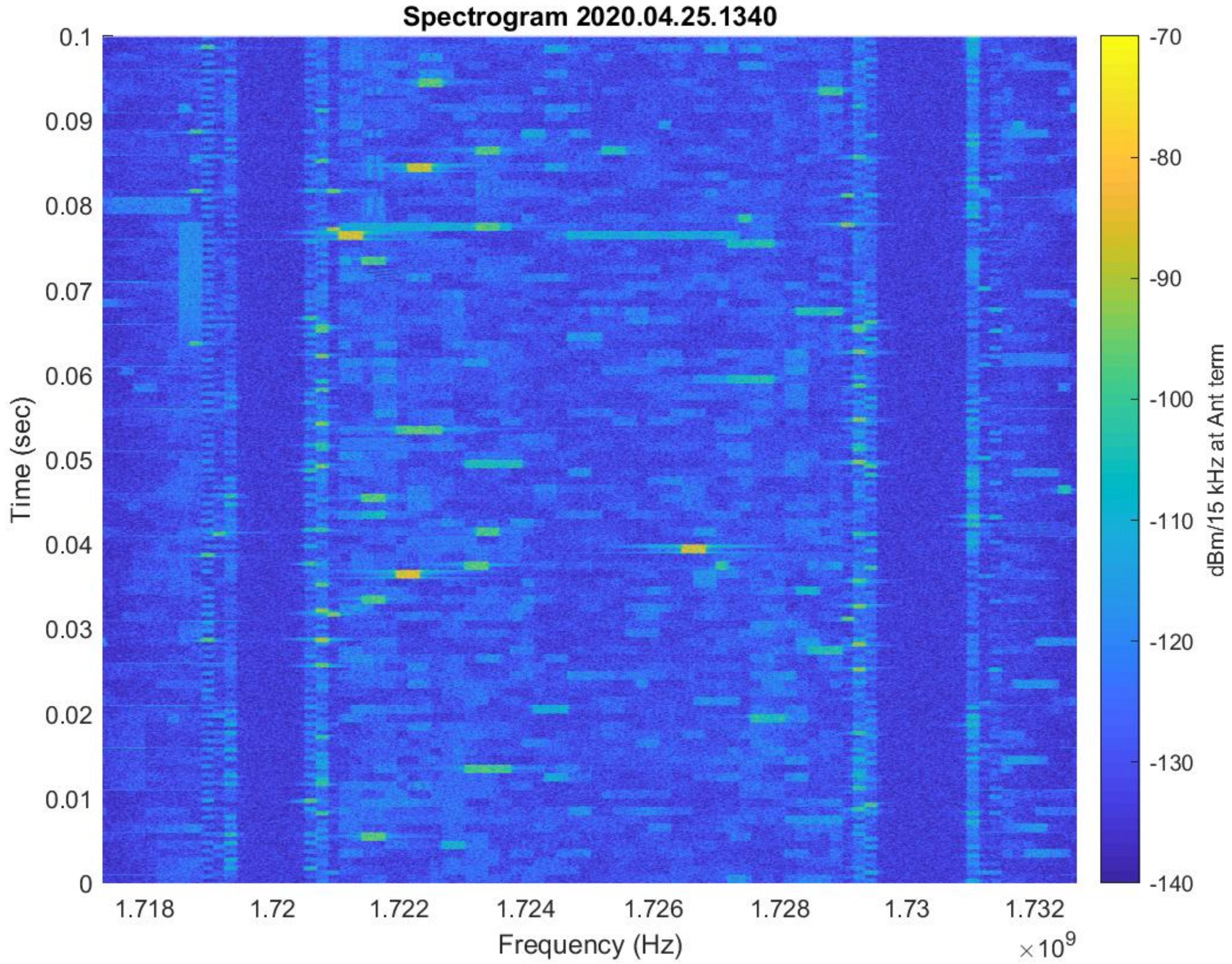
Panel Antenna Coverage in Grand Jct, CO

azimuths and beamwidths indicated



As a basis for comparison…

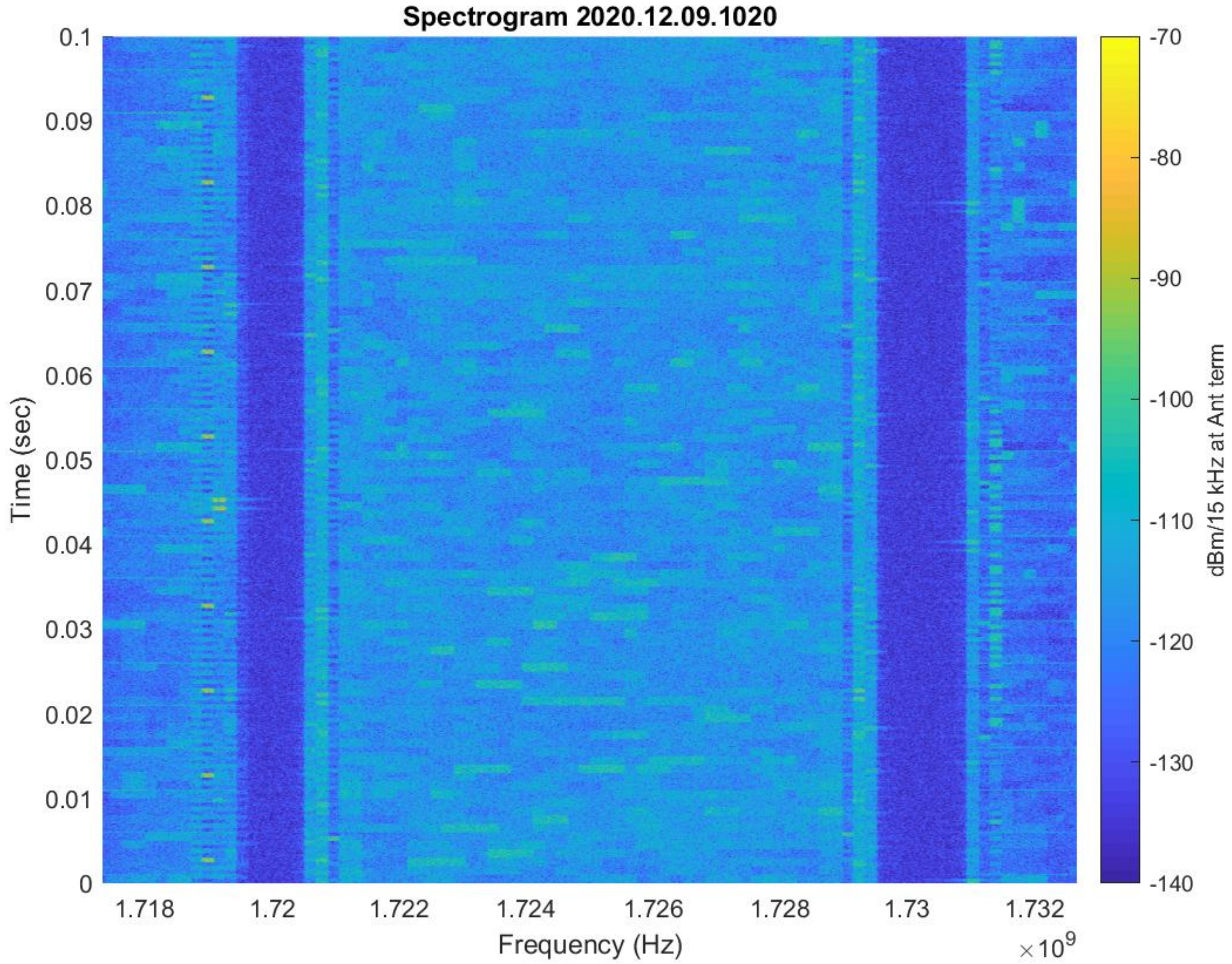
- ITS aggregate interference system characteristics:
  - Panel antenna has a 33° horizontal beamwidth and 20.5 dBi gain
  - Preselector has LNA preceded by 60 MHz bandpass filter, which only encompasses the AWS-1 uplink
  - Standoff distance is typically 7-10 km and encompassed population ranges from 50,000 to well over 500,000
  - UEs are served by tens to hundreds of eNBs, so aggregate PRB occupancy during daytime hours is routinely 100%
- The in-situ measurements had these differentiators:
  - Employed a narrow-beam dish antenna
  - Front end filter is much wider—approximately 1370-2560 MHz
  - At EAFB assessed victim receive system with VSA tapped in adjacent to AMT receiver



Longmont, CO

10 MHz LTE band

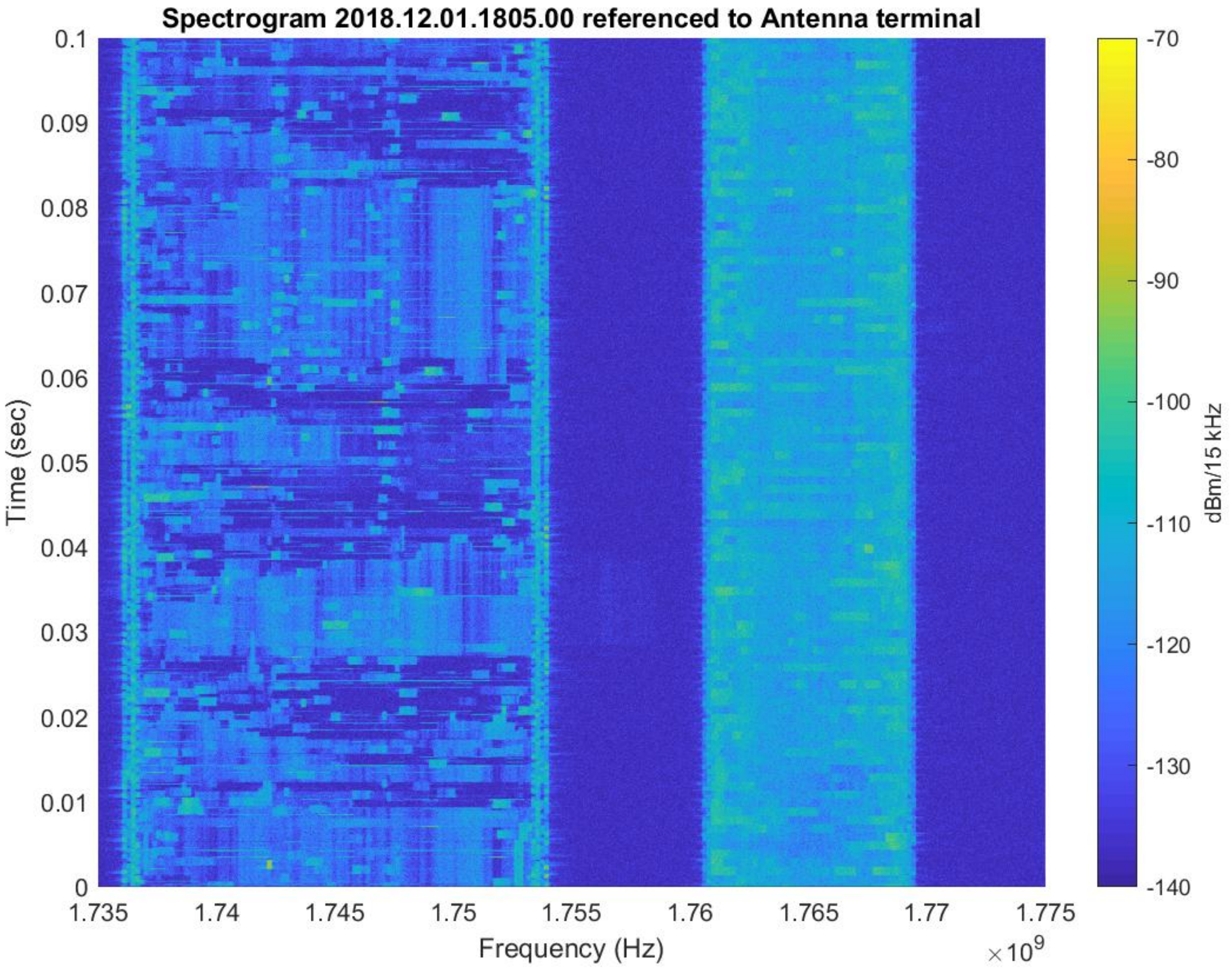
(center)



Denver, CO

10 MHz LTE band

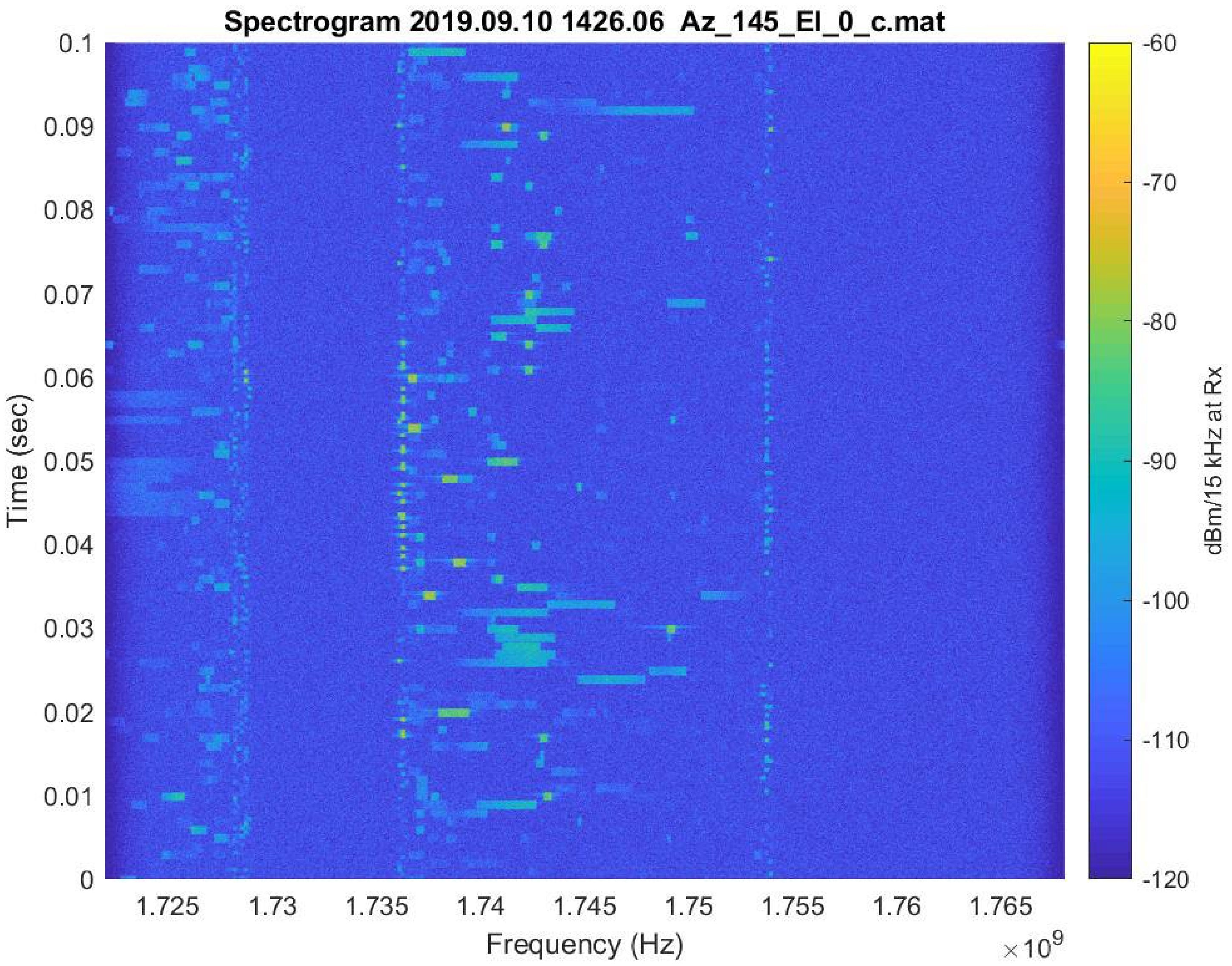
(center)



In-building DAS at Mercedes Benz Stadium, Atlanta, GA

10 MHz LTE band (right)

20 MHz LTE band (left) is an external macrocell



Edwards AFB

20 MHz LTE band (center)

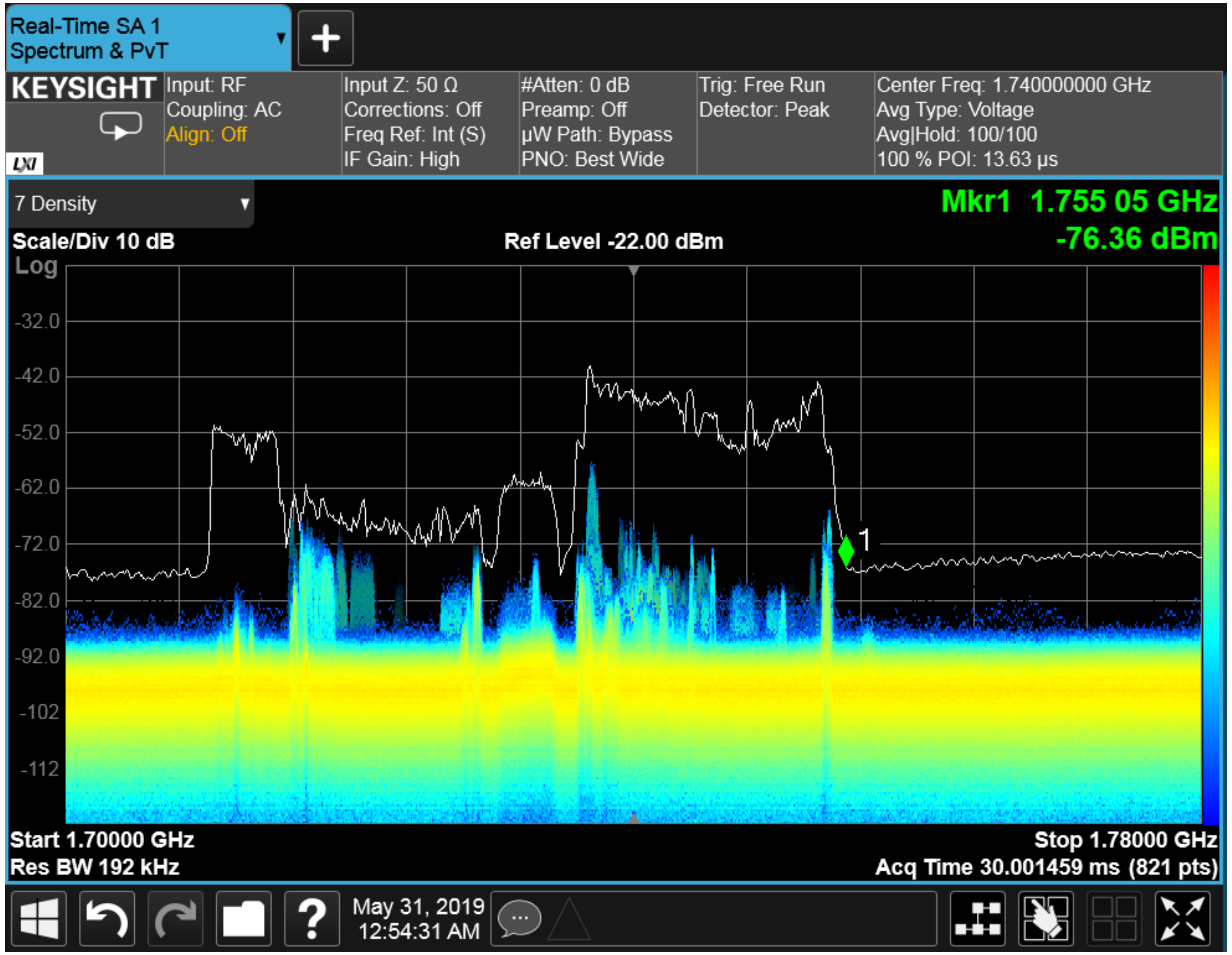
Aggregate measurements of larger populations with wide beamwidth antenna permit AWGN assumptions

Narrow beamwidth in-situ AMT captures demonstrate need for lab testing to characterize and model emissions

Site Survey

- Assess the characteristics of the RF chain and any presence of strong in-band transmissions
- Demonstrate that the AMT receiver’s front-end LNA determines the receive system noise figure, i.e. the VSA’s internal noise is negligible
- Examine worst case scenario with AMT antenna at 0° elevation. Slew antenna through all azimuths and note azimuths with stronger UE transmissions
- Revisit noted azimuths and dwell for several minutes to gauge level of activity
- Map each noted azimuth to ascertain possible sources; investigate source(s)
  - Intermittent transmissions were often associated with vehicles on rural highways
  - Periodic transmissions were often associated with office buildings or nearby developments
  - Regular transmissions were typically from distant cities

Azimuthal Scanning and Source ID



Real Time

SpecAn Display

Antenna Control
and Camera

Note: instrument noise floor is driven by front end LNA

Azimuthal Scan Mapping

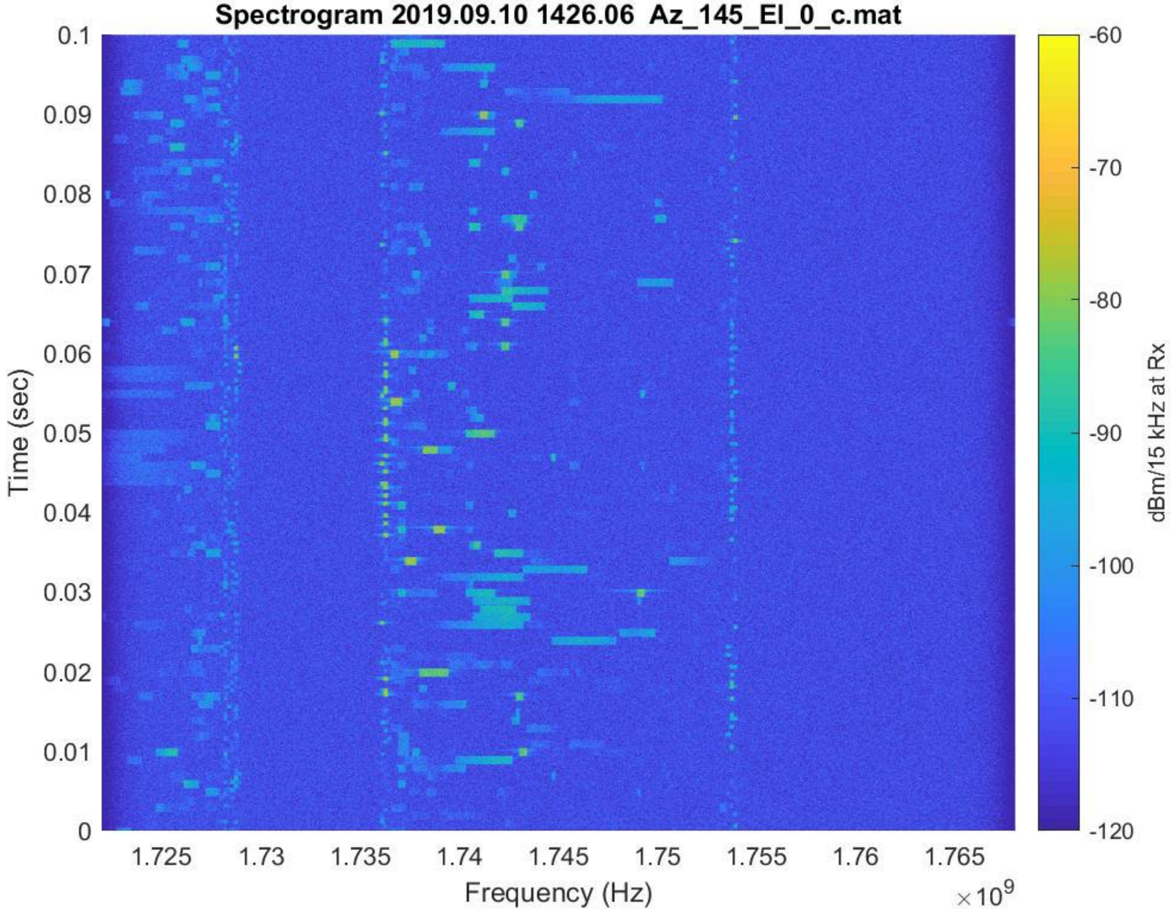
Edwards AFB

NASA LaRC

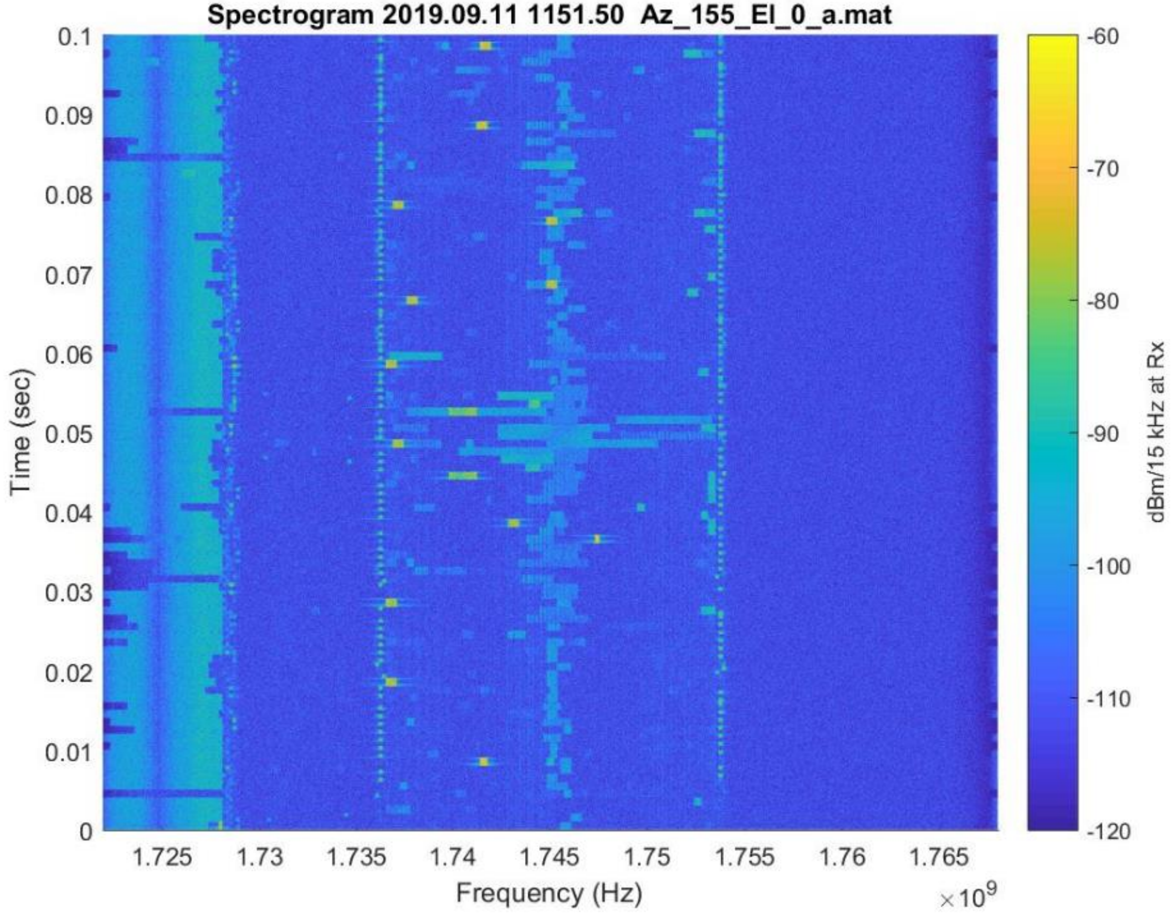
In-Situ Measurement Approach

- Revisit worst case azimuths noted during site survey
- Capture UE transmissions from uppermost AWS-1 LTE band
- Increase VSA span to ensure capture of upper adjacent-band emissions
- Using a test UE, generate emissions with known throughputs into antenna sidelobes
- Measure G/T using the sun as a noise source (EAFB) or net loss from the antenna to the VSA input (NASA/LaRC) to provide a gauge to estimate UE transmit power

Sample over-the-air captures



Edwards AFB



NASA LaRC

Single UE Captures

NASA LaRC

Requested data rate	Reported data rate
100 kbps	100.5 kbps
1 Mbps	999.6 kbps
5 Mbps	4997.8 kbps
10 Mbps	9962.1 kbps
20 Mbps	19578.4 kbps
50 Mbps	49294.2 kbps*

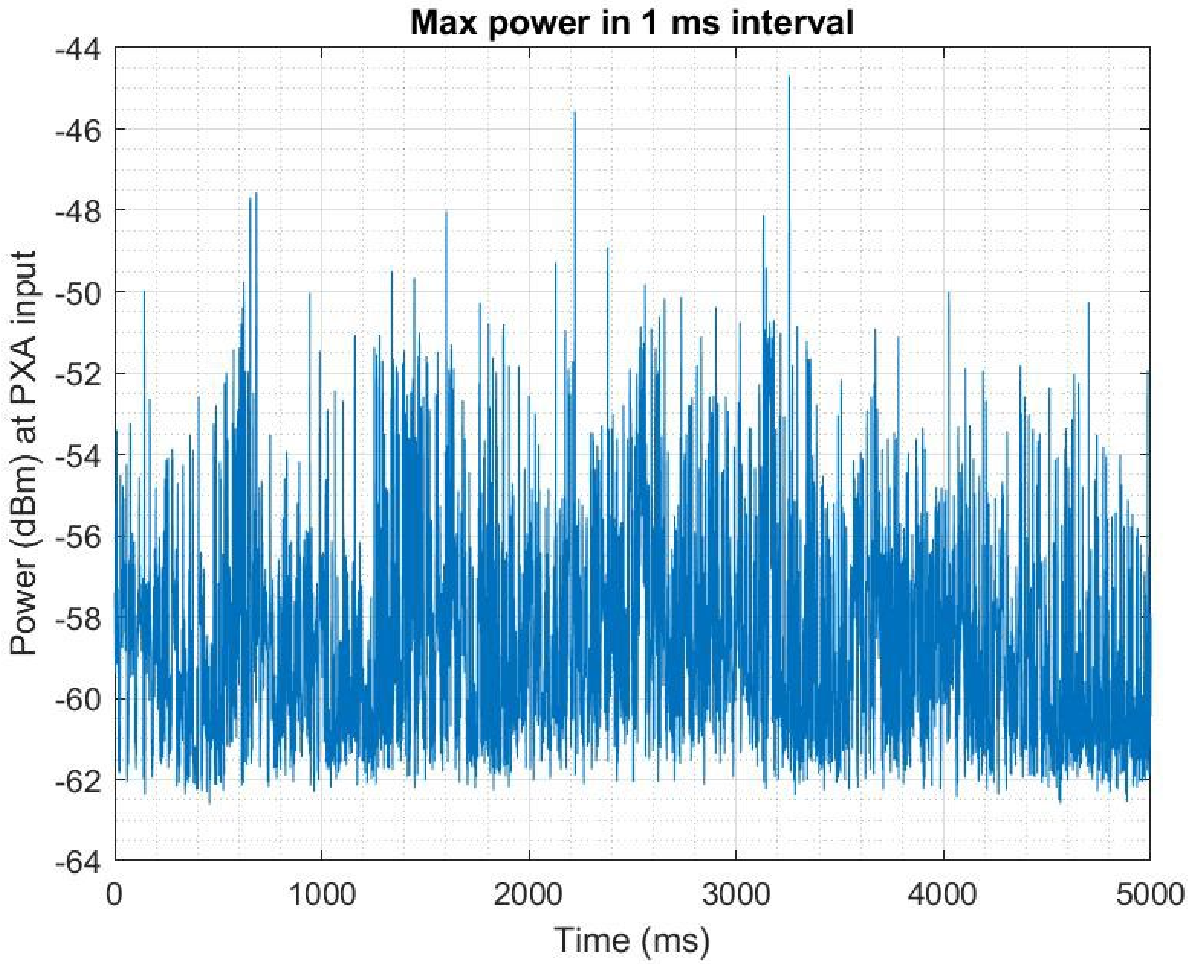
* bandwidth not obtained as indicated by traffic monitoring tool

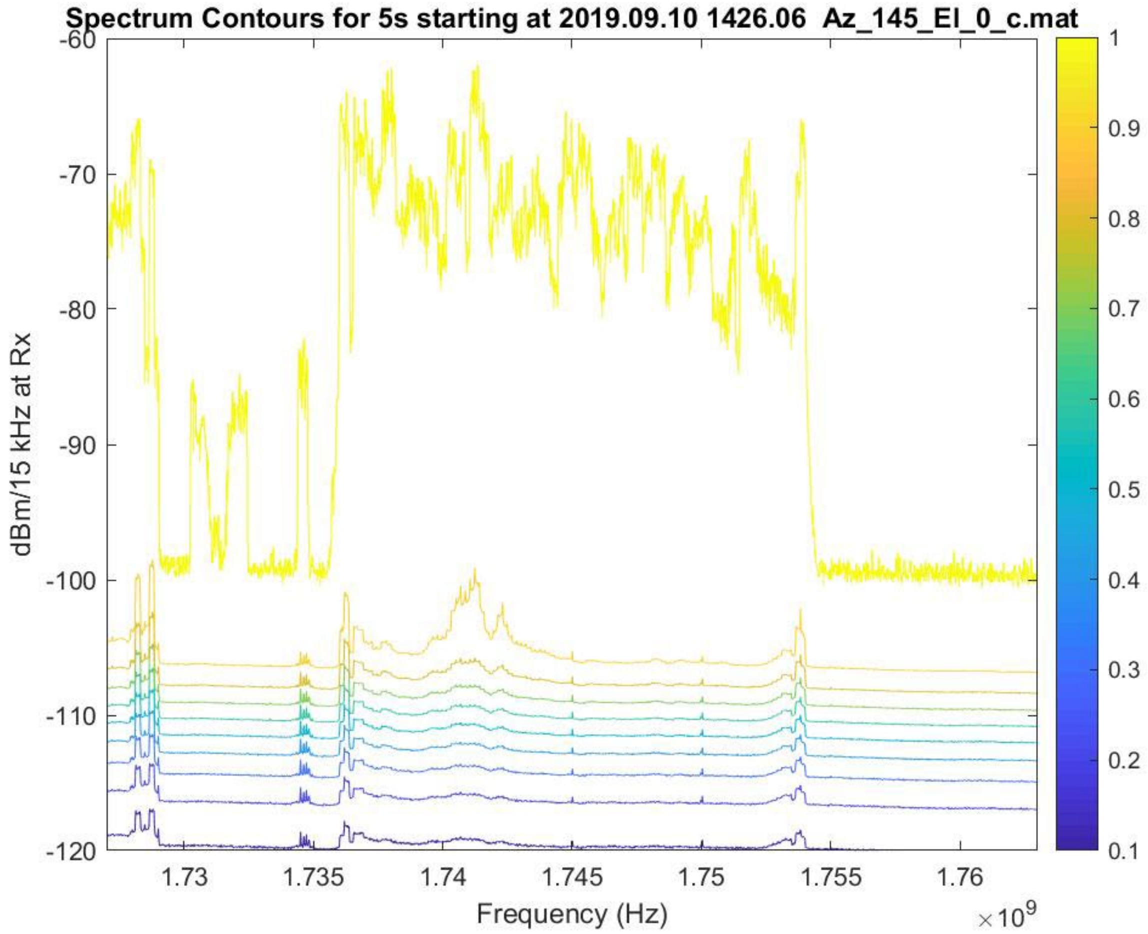
Edwards AFB

Capture Post-Processing

- Spectrograms are optimal for observing UE activity in a band, but the LTE transmission time interval (TTI) of 1 ms imposes a practical limit of 100 ms per plot making hundreds of plots necessary.
- Spectrogram contours indicate decile power thresholds for each of the FFT bins and are a useful summary—especially for illustrating out of band emissions and peak powers.
- A single sample exceeding the VSA’s Input Range will flag an overload. The instrument has several dB of headroom, so Power vs. Time plots provide insights into overload conditions during a capture.

Power vs. Time and Spectrum Contour Plots

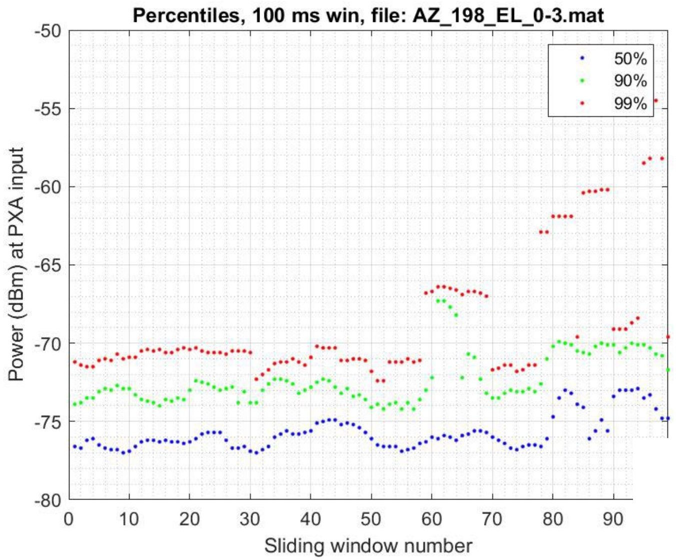


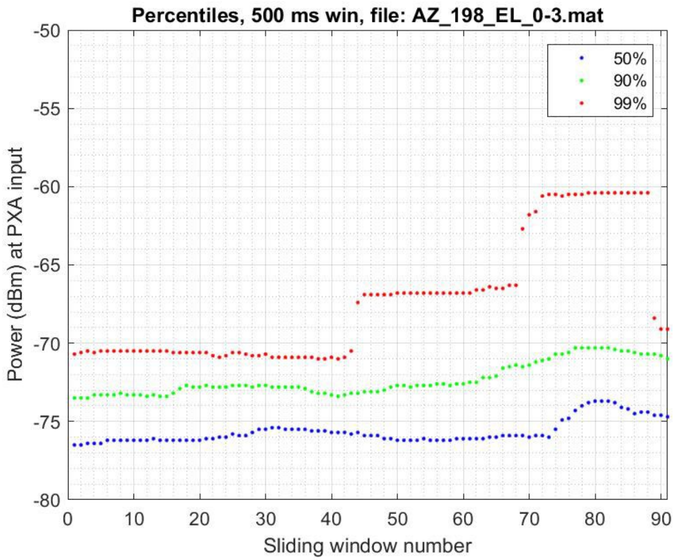


Selection of Waveforms for Bench Testing

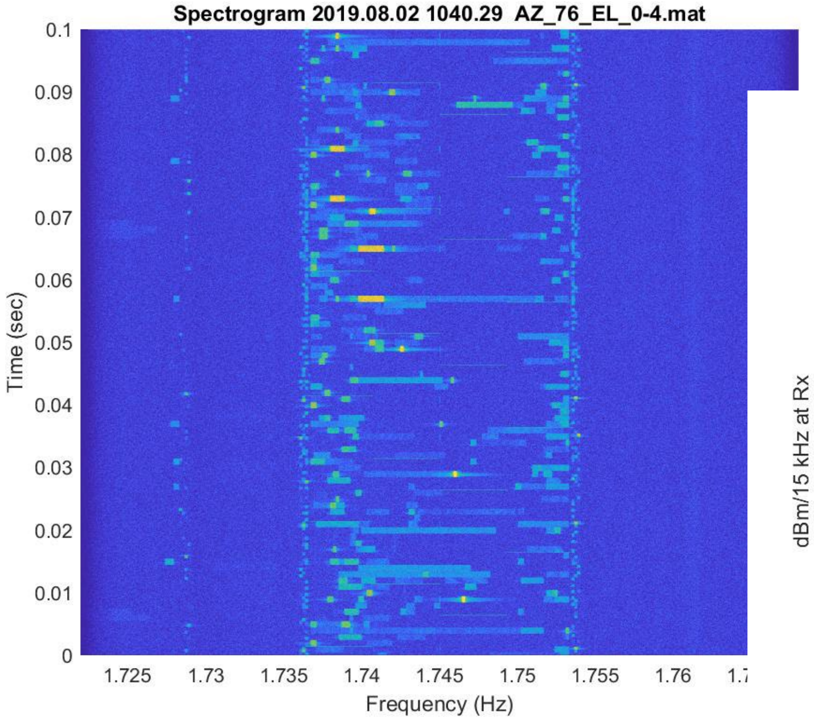
Sliding Window Technique

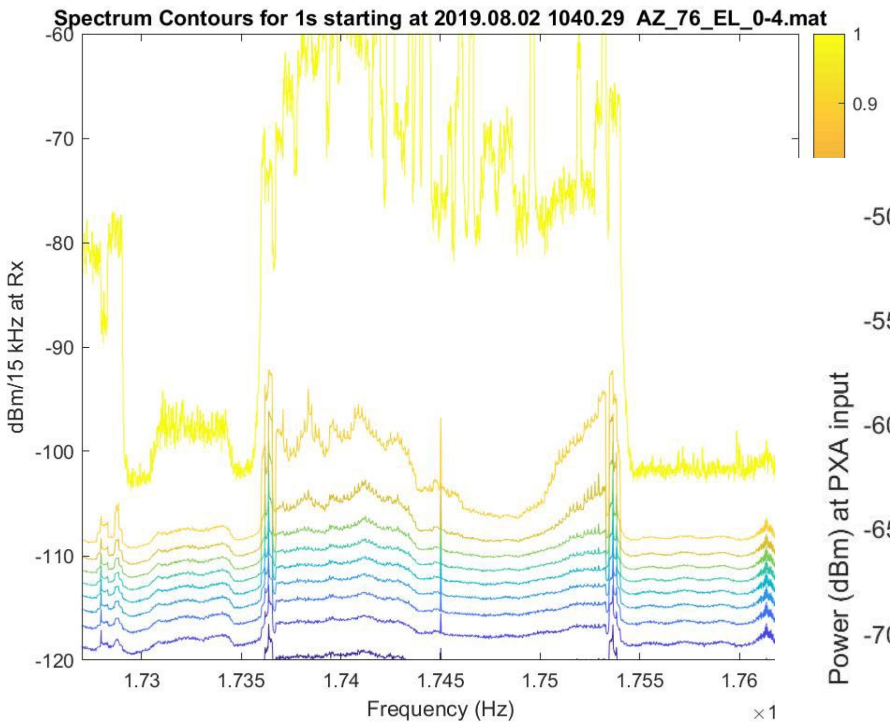
- Start with the 3072 x (N/3072) FFT array which represents power in mW per 15 kHz bin;
- For each FFT sum linear power across the bins within the 18 MHz occupied bandwidth which in this instance was the center 18,000/15 = 1200 bins;
- From this result which contains 15 power measurements per ms, compute the cumulative density functions (CDFs) for windows ranging in size from 100-1000 ms or 1500-15000 samples, slid through the data sequence in 50 ms overlapping steps;
- Determine the 50th, 90th, and 99th percentile power for each window; and
- Plot the percentiles as a function of window number.

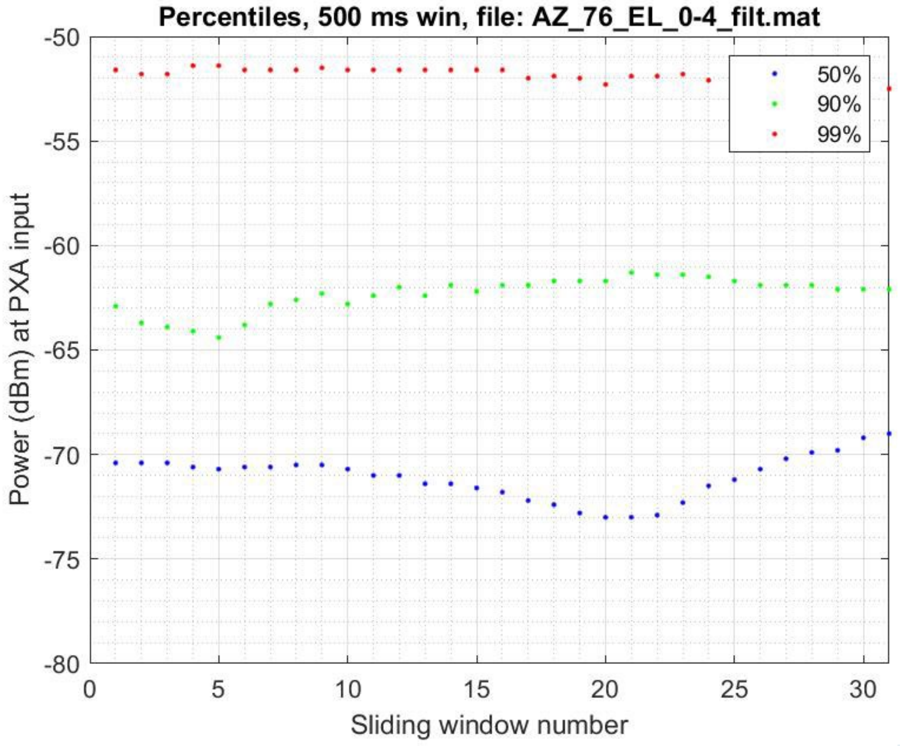




Multi-UE (Live) Waveform Artifacts

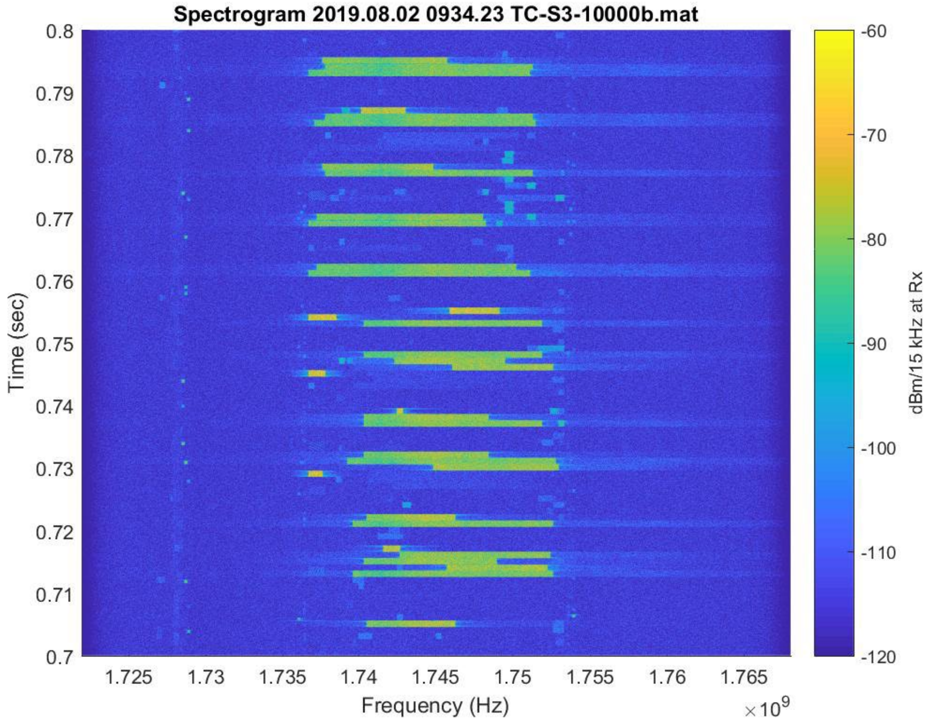


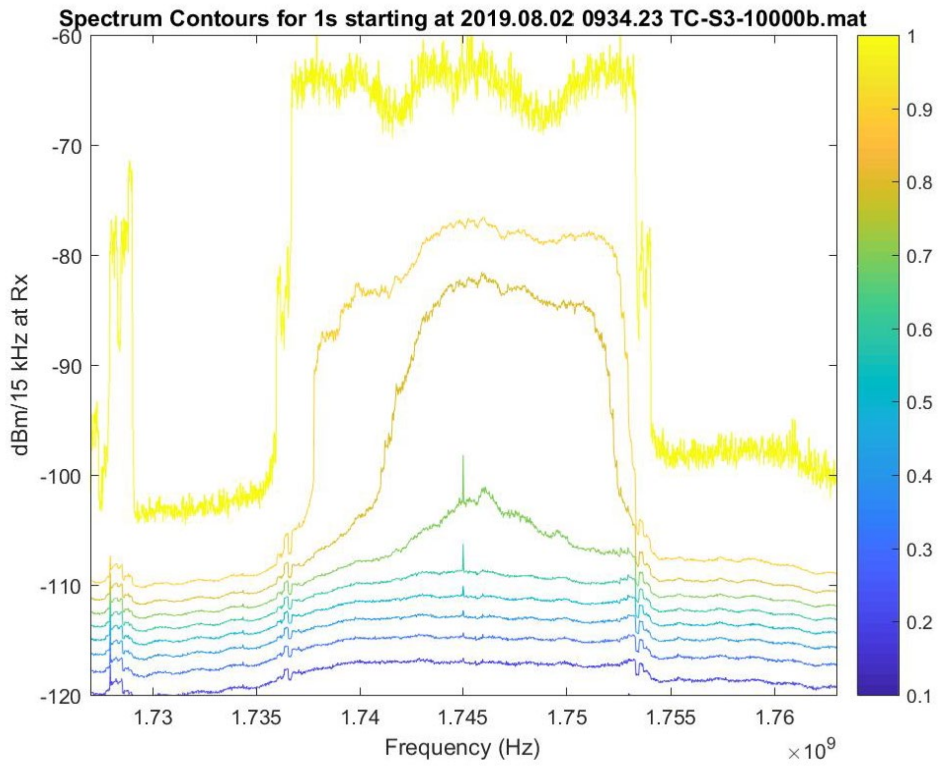




One of 4 waveforms (2 each from EAFB and NASA/LaRC)

Single (Test Mode) UE Waveform Artifacts





UE upload rate of 10 Mbps

Conclusions

- Use of AWS-1 as a proxy for AWS-3 continues to foster ongoing research as wireless carrier LTE deployments in AWS-3 lag those in AWS-1
- In-situ captures evidence dramatically reduced band occupancy (versus wider beamwidth antennas) and demonstrate the need for controlled experiments with eNBs
- Mature VSA capture and post-processing techniques yield test waveforms that illustrate the impact of real-world UE emissions through controlled bench testing

- References

  - E. D. Nelson, “LTE Uplink Aggregate Interference Measurement System,” NTIA Technical Memorandum TM-21-552, February 2021,
  - Eric D. Nelson and Duncan A. McGillivray, “In-Situ Captures of AWS-1 LTE for Aeronautical Mobile Telemetry System Evaluation,” NTIA Report TR-21-553, March 2021

Task 2
Laboratory Methods for Recording AWS-3 LTE Waveforms

Presented by:

Duncan A. McGillivray, NIST

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Purpose

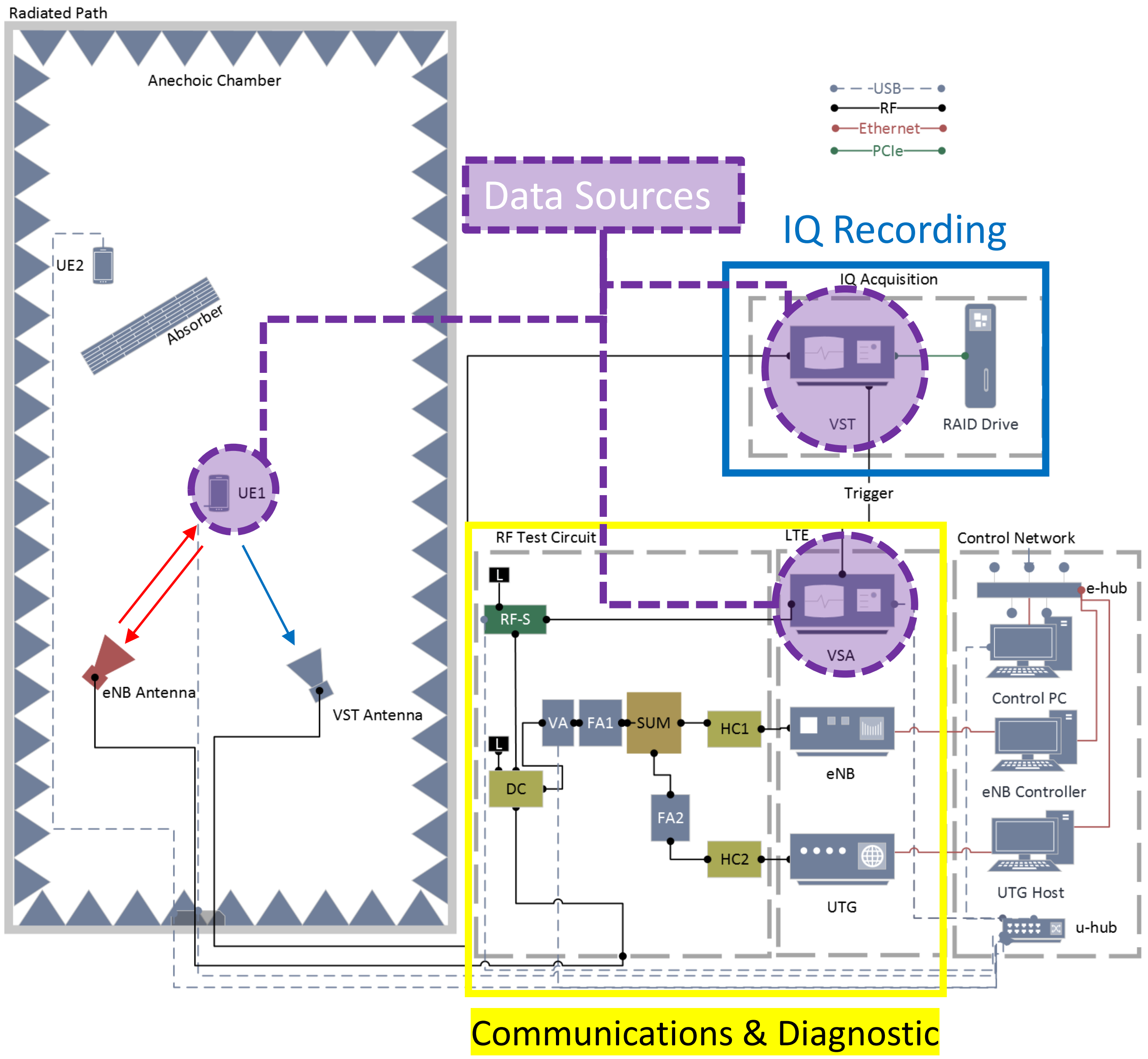
Record Radiated Waveforms for Receiver Sensitivity and Susceptibility Testing

a. Leverage existing equipment and test benches to generate and capture LTE – UL waveforms
b. Develop & measure various radiated test scenarios
c. Establish a "Library of LTE – UL waveforms" that can be leveraged for AWS-3 LTE Impacts on AMT and future tests

- Experimental Setup
- Experimental Design
- Data Synchronization and Validation
- Library

Anechoic Chamber LTE UE Measurements

- Communications and Diagnostic
  - Hybrid – cabled & over the air testbed controls test factors:
    - Pathloss to DUT
    - RF condition of Traffic Generator
  - Cellular traffic parameters
    - DUT UE data rate
    - Background traffic of the eNB cell
  - Monitoring of LTE diagnostics at the DUT UE and uplink (UL) traffic close to the eNB
  - Records
    - UE diagnostics
    - Spectrum occupancy
- IQ recording
  - Separate path
  - Electronically triggered
  - Optimized for dynamic range



IQ Capture Scenarios

Factor	# Levels*	Settings	Type	Testbed Component
Power control	2	Open Loop / Closed Loop	categorical	eNB
Allocation	3	5, 10 , 20 MHz	numeric	eNB
Resource Block (RB) blanking mask	4	None, Upper 6 RBs, Upper 10 RBs, Center 10% RBs	categorical	eNB
DUT UL data rate	4	0.5, 1, 5, 10 Mbps	numeric	DUT UE
# loading UEs	3	3, 7, 15	numeric	Traffic Generator
# radiating UEs	2	1, 2	numeric	NBIT
*Test scenarios not fully factorial				

- Static Settings:
  - IQ Recording
    - 61.44 M Samples/s
    - Length: 5 seconds
  - eNB
    - P0 PUSCH -85 dBm
    - P0 PUCCH -117 dBm
    - alpha 0.8
  - DUT UE-primary
    - traffic type: UDP
    - RSRP: -95 dBm
  - DUT UE-secondary
    - 0.5 Mbps uplink rate
    - traffic type: UDP
    - RSRP: -115 dBm
  - Background Traffic
    - 0.5 Mbps per loading UE
    - traffic type: UDP
    - RSRP: -95 dBm

56 unique configurations; 5 seconds recordings; each recorded twice

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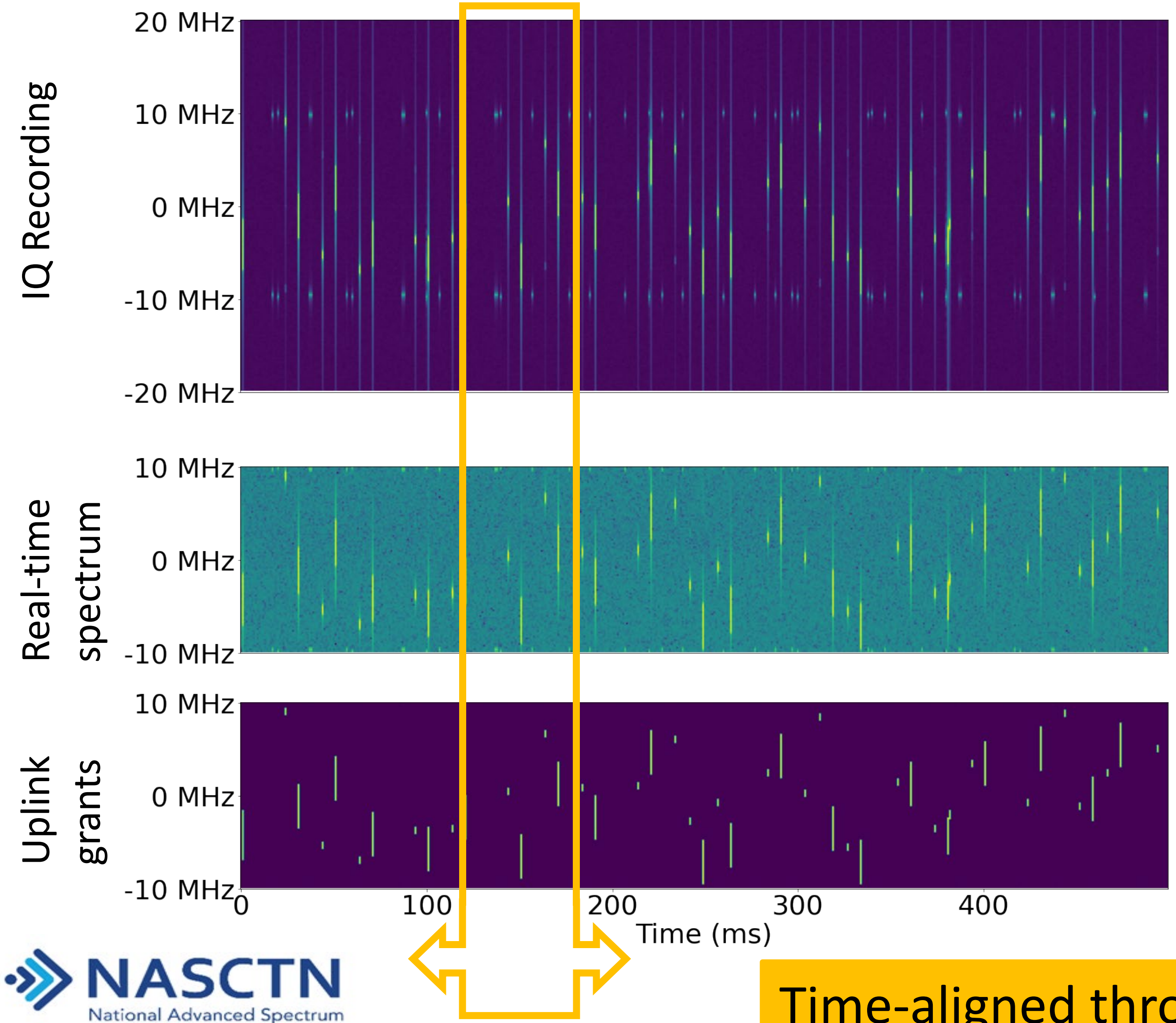
Data Synchronization and Validation



- IQ recording
  - Published as
    - interleaved 16 bit integer
    - spectrogram (dB/RB)
    - referenced to -25 dBm
- Real-time spectrum
  - Not published
    - Used as cross confirmation that VST and USRD are recording the same events
- UE Diagnostic
  - Published as
    - Diagnostic spectrogram (mW/RB)
    - Time series of
      - uplink grant size & location (Start RB, # of RBs)
      - MCS index (integer)
      - Total Power per TTI (dBm)

Time-aligned through autocorrelation

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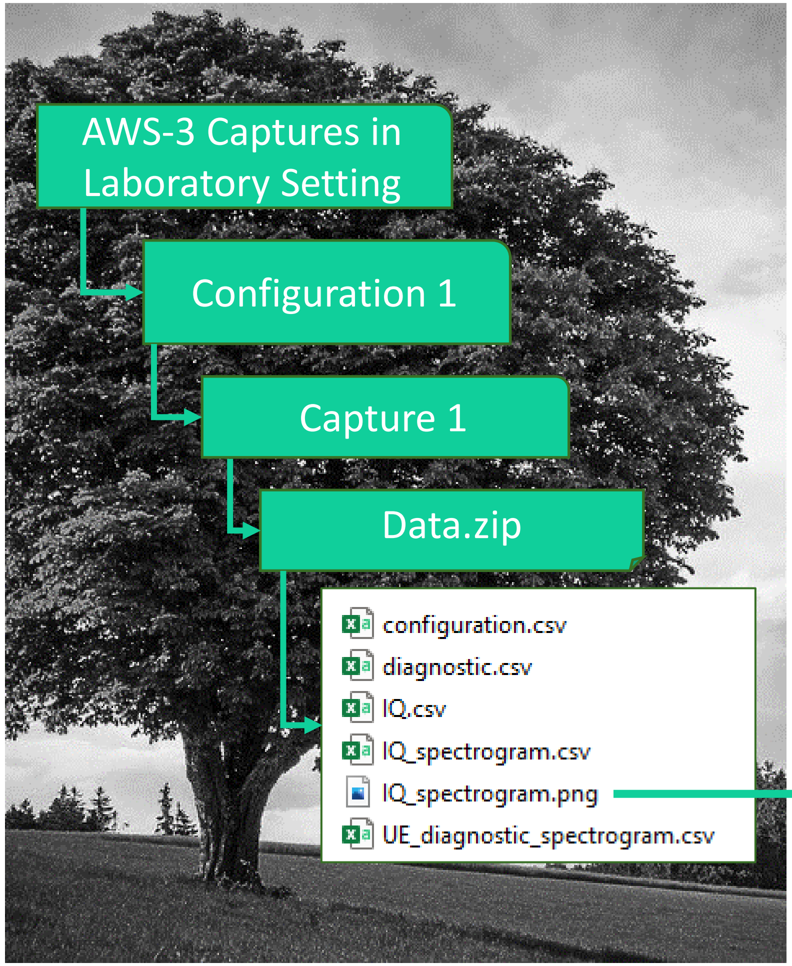
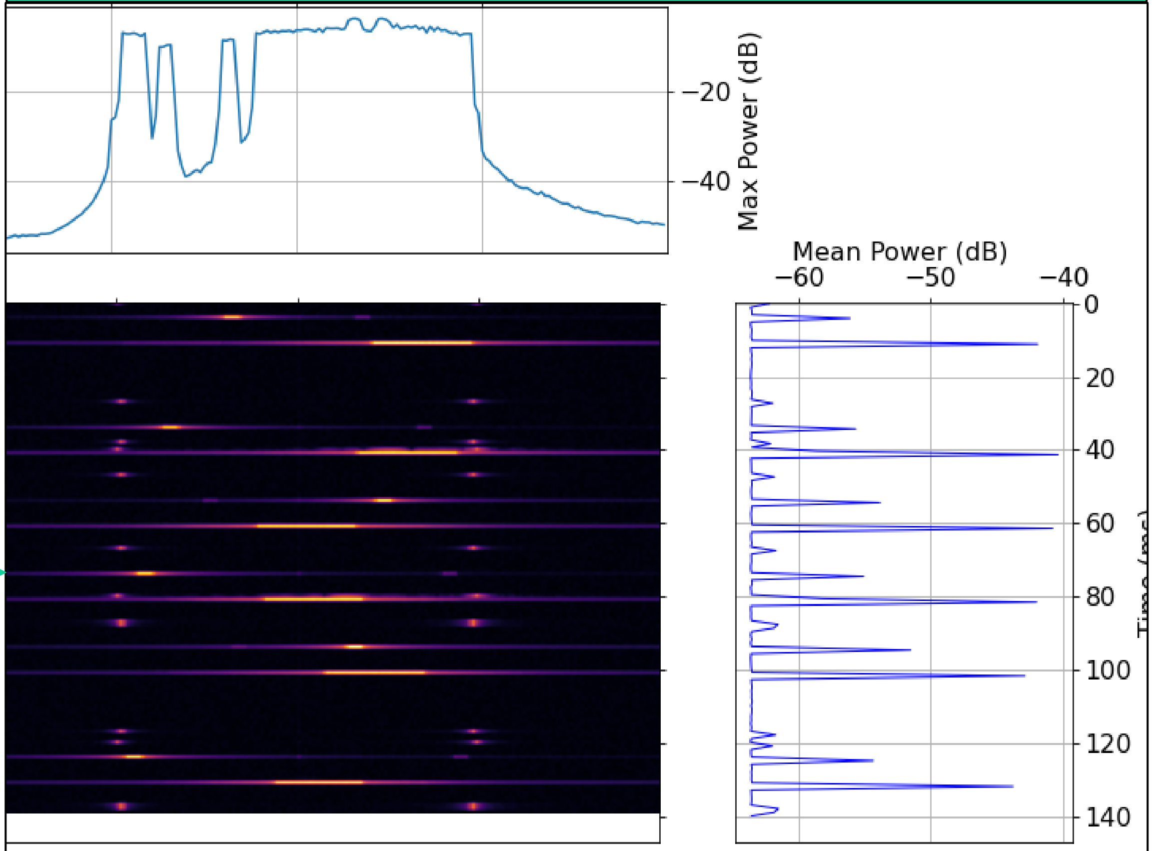
IQ Library



140 millisecond snapshot of 5 second recording



Power Control	Resource Blanking	Allocation
CLPC	None	20 MHz
DUT UE Data Rate	**Number Loading UEs**	**Number Radiating UEs**
500 kbps	15	1

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Task 3
AWS-3 LTE Impacts on Aeronautical Mobile Telemetry

Presented by:

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Outline

- Testbed Design & Characterization
- Experiment Design
- Waveform Processing
- Susceptibility Study
  - Frequency Offset Experiment: IRIG-based Analysis
  - Selected Results from Main Characterization Experiment
  - Equivalent Ambient Noise (E_b/N_0 Loss) Analysis
- Anomalous Results
- Conclusions

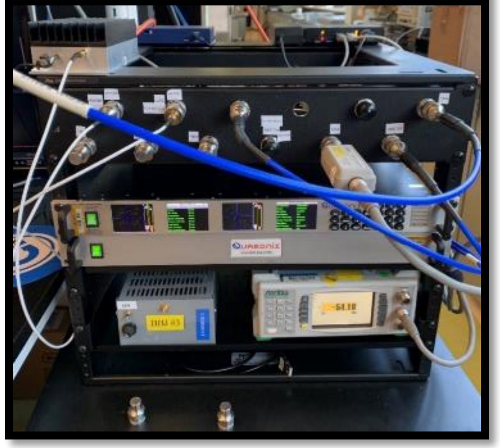
Testbed Design & Characterization

Highlights

- **MITRE, Bedford MA**
  - Lead testbed for
    - Test execution
    - Automation development
- **NIST, Boulder CO**
  - Lead concept development of
    - Experiment Design
    - Test Profiles

> - Efficient traversing of test design with multiple degrees of freedom
> - Parallel acquisition of test matrix
> - High degree of consistency in results
> - Confidence in investigation of anomalous results

MITRE, Bedford MA



NIST, Boulder CO

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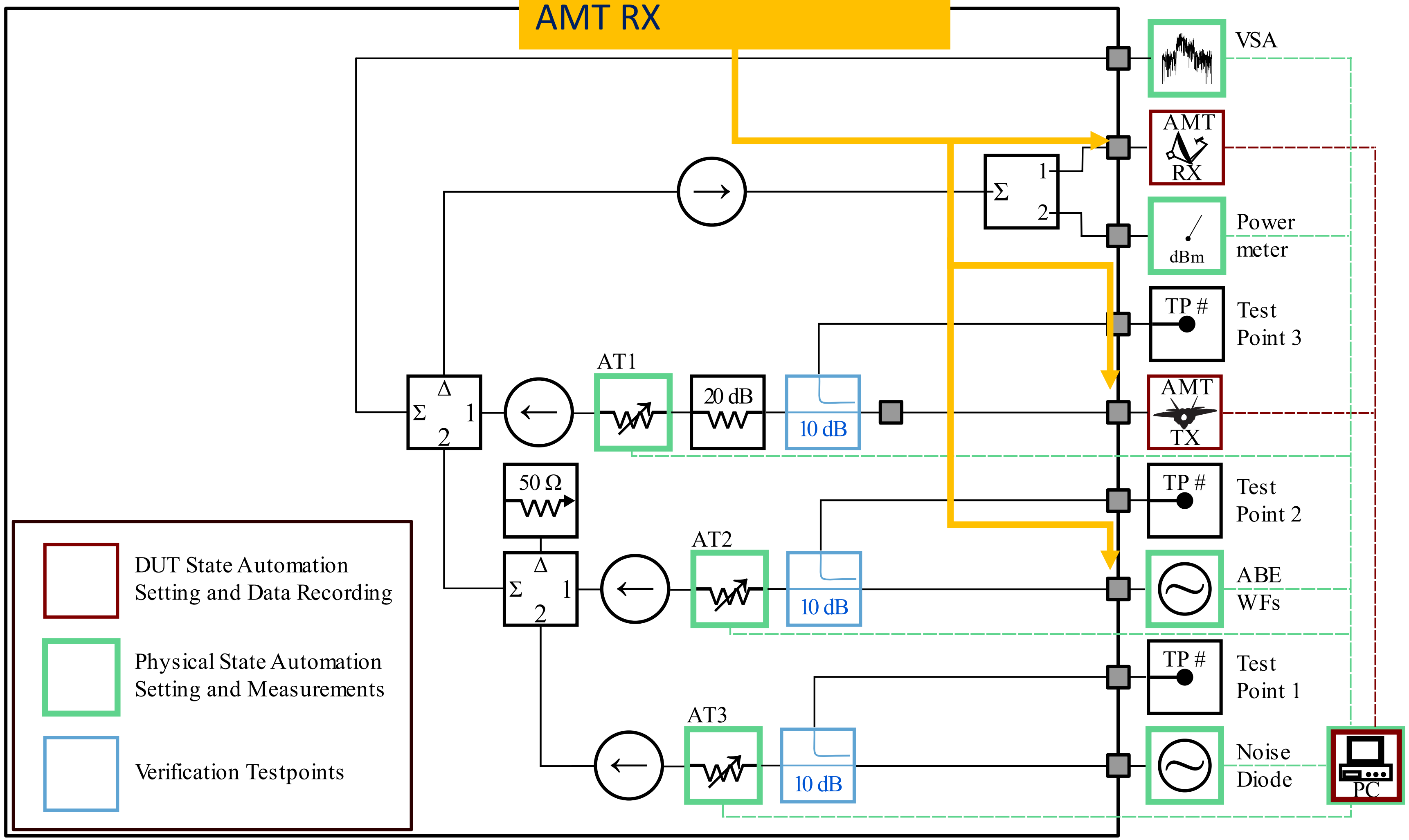
Test Circuit

AMT TX and ABE Referenced to input of AMT RX



- Shared
  - RF circuit componentry
  - Test automation framework
  - Calibration source
- Differences
  - AMT TX
  - ABE waveform generator
  - Power meter
  - VSA

Testbed characterization

- Characterized
  - sources for power output and variability across all test design factors
  - variable attenuator performance
- Quantified test circuit path loss
- Investigated receiver noise performance
- Performed rigorous uncertainty estimation for:
  - Aeronautical Mobile Telemetry (AMT) Signal Power at the plane of the AMT receiver (RX)
  - Adjacent band emissions (ABE) signal power at the receiver for both additive white Gaussian noise (AWGN), Long-term Evolution (LTE)
  - AMT Signal to ABE Power ratio (SABE) at the plane of the AMT receiver (RX)

Table A.9: Summary of expanded uncertainty values for the various test conditions referenced to the N-type RF input connector of the AMT receiver

Testbed Location	AMT Signal Power at RX Uncert. (dB)	ABE Signal Power at Rx ABE Type	ABE Signal Power at Rx Uncert. (dB)	SABE at RX Uncert. (dB)
Bedford	±0.98	AWGN	±1.02	±2.00
		LTE	±1.19	±1.98
Boulder	±0.90	AWGN	±0.89	±1.79
		LTE	±1.13	±1.84

Experimental Design

Overview of Experiments

- Pre-testing (a.k.a. sensitivity testing)
  - Early-stage investigations to inform test procedures & test automation
- Seven designed experiments – further details in Chapter 2 of tech report
  - Pilot Study: Baseline Experiment, Characterization Experiment
  - Frequency Offset Experiment
  - Main Characterization Experiment
  - Supplemental Experiments
    - Side Experiment A: Equalizer
    - Side Experiment B: Space-Time Coding
    - Side Experiment C: Excess Noise

Pilot Study

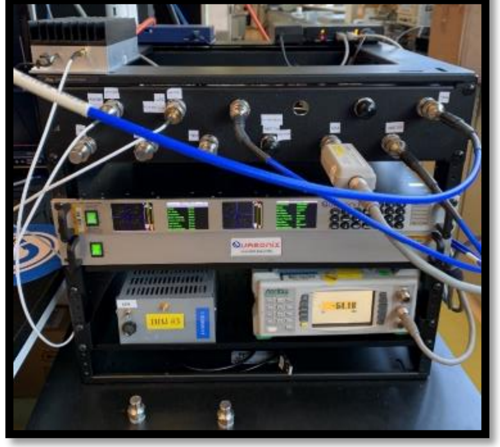
Goals:

1) **Verify testbed automation (on two testbeds)**
2) **Obtain preliminary data to inform subsequent experiments**

- Baseline Experiment (Repeatability Assessment)
  - 2 factors, fixed receiver settings, 33 unique test configs
  - Repeated 7 times
- Characterization Experiment
  - 6 factors, 1320 unique test configs
- First NASCTN implementation of parallel testbeds
  - Led to improvements in testbed automation software
  - Informed selection of factors and signal levels for main characterization experiment (described next)

NIST, Boulder CO

MITRE, Bedford MA



Frequency Offset Experiment

Objective: Characterize effect of shifting AMT center frequency relative to ABE

Id	Factor	Settings	# Levels	Easy/Hard to Change
A	Modulation Type	PCM/FM, SOQPSK, SOQPSK-FEC, ARTM-CPM	4	Hard
B	Bit Rate	1, 5, 10 Mbps	4	Hard
C	ABE Type	AWGN 20 MHz, in-situ LTE captures: single-UE (92 RB, Full, 92 RB filtered, Full filtered), multi-UE: (EAFB Az76, EAFB Az198), lab LTE captures (20 MHz Full, 20 MHz upper 10 RB blanked, 5 MHz Full)	10	Hard
D	Frequency Offset	1 MHz steps on grid including IRIG-recommended offset	12	Hard

- Only test Modulation/Bit Rate combinations shown in yellow
- Same S_{ave}/ABE_{peak} ratio for each LTE waveform
- S_{ave}/ABE_{ave} fixed for AWGN
- <u>840 unique test configurations</u>
- Repeats/replication
  - All configurations tested twice at MITRE-Bedford
  - Subset tested twice at NIST-Boulder (excluding SOQPSK-FEC)

Modulation Type	Bit Rate (Mbps)			
PCM/FM	1	5		
SOQPSK		5	10	
SOQPSK- FEC		5	10	
ARTM CPM		5		

Main Characterization Experiment

Objective: Assess impact of different ABE types on AMT receiver performance. Cover transition from strong link (BER < 10^{-7}) to a poor link (BER > 10^{-4})

Id	Factor	Settings	# Levels	Easy/Hard to Change
A	Modulation Type	PCM/FM, SOQPSK, SOQPSK-FEC, ARTM-CPM	4	Hard
B	Bit Rate	1, 5, 10, 20 Mbps	4	Hard
C	ABE Type	None, AWGN (BW=20, 18, 16.5 MHz), in-situ LTE captures: single-UE (92 RB, Full), multi-UE (EAFB Az76, EAFB Az198, LaRC Az140, LaRC Az165)	10	Hard
D	AMT Signal Level	1 dB steps on grid spanning a 10 dB range with config-dependent shift	11	Easy

- Configurations not tested:
  - PCM/FM at 20 Mbps, ARTM-CPM at 1 Mbps
- 1540 unique test configurations
- Repeats/replication
  - All configurations tested twice at MITRE-Bedford
  - Subset tested twice at NIST-Boulder (excluding SOQPSK-FEC)

Modulation Type	Bit Rate (Mbps)			
PCM/FM	1	5	10	
SOQPSK	1	5	10	20
SOQPSK- FEC	1	5	10	20
ARTM CPM		5	10	20

First priority shown in yellow

Supplemental Experiments

- Address emerging aspects of AMT receiver operations and susceptibility testing – details and results in tech report
- **Side Experiment A: Equalizer**

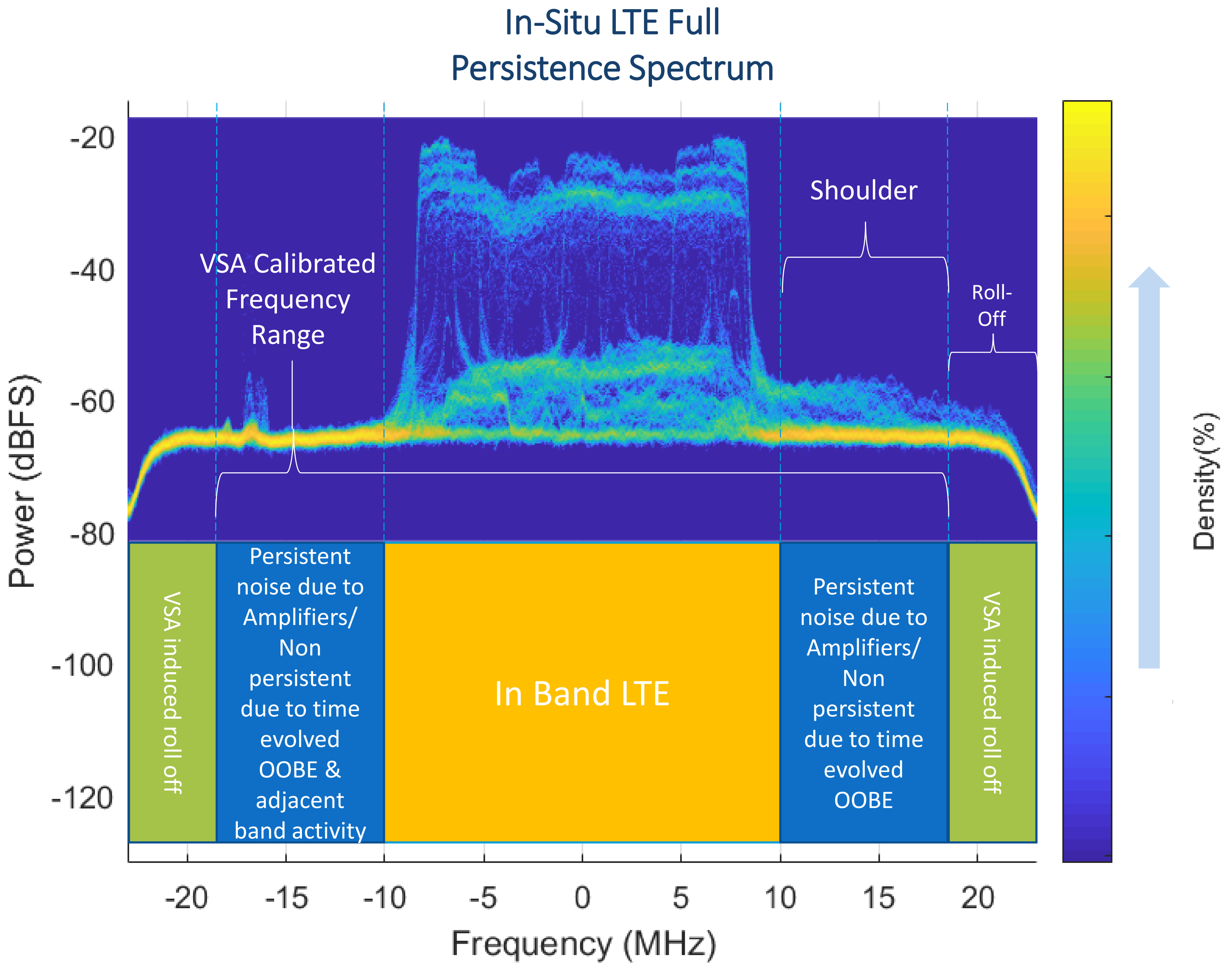
  Objective: Assess impact of enabling equalizer in the presence of ABE
- **Side Experiment B: Space-Time Coding**

  Objective: Assess impact of STC option in the presence of ABE
- **Side Experiment C: Excess Noise**

  Objective: Assess impact of in-band excess white noise on AMT performance

Waveform Processing

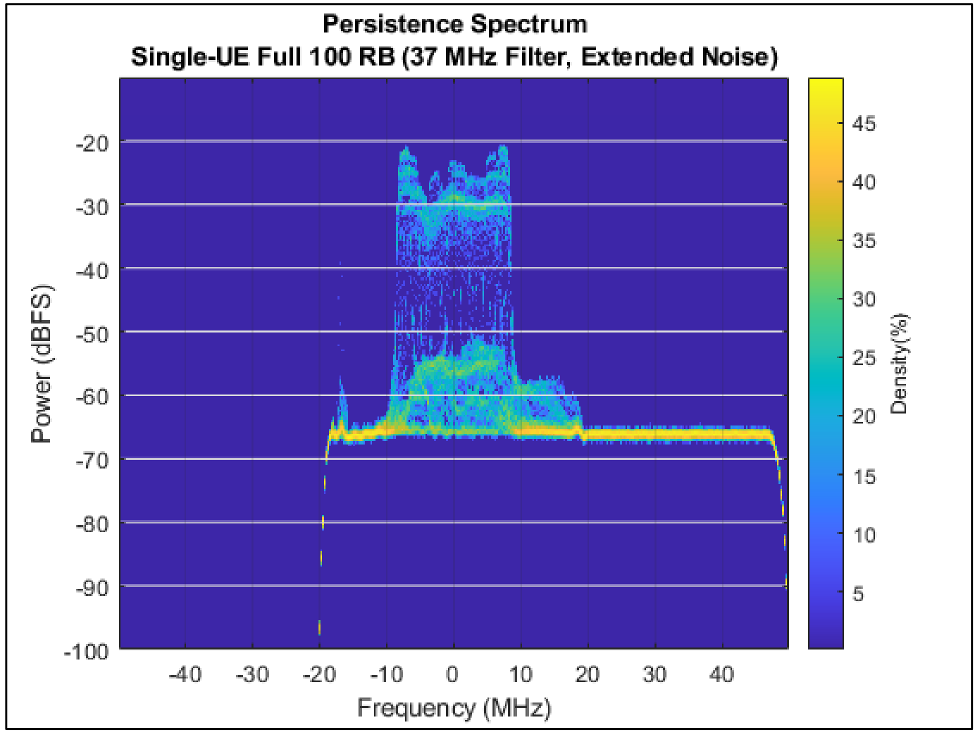
As Captured Waveforms



Adjacent Band Waveform Review

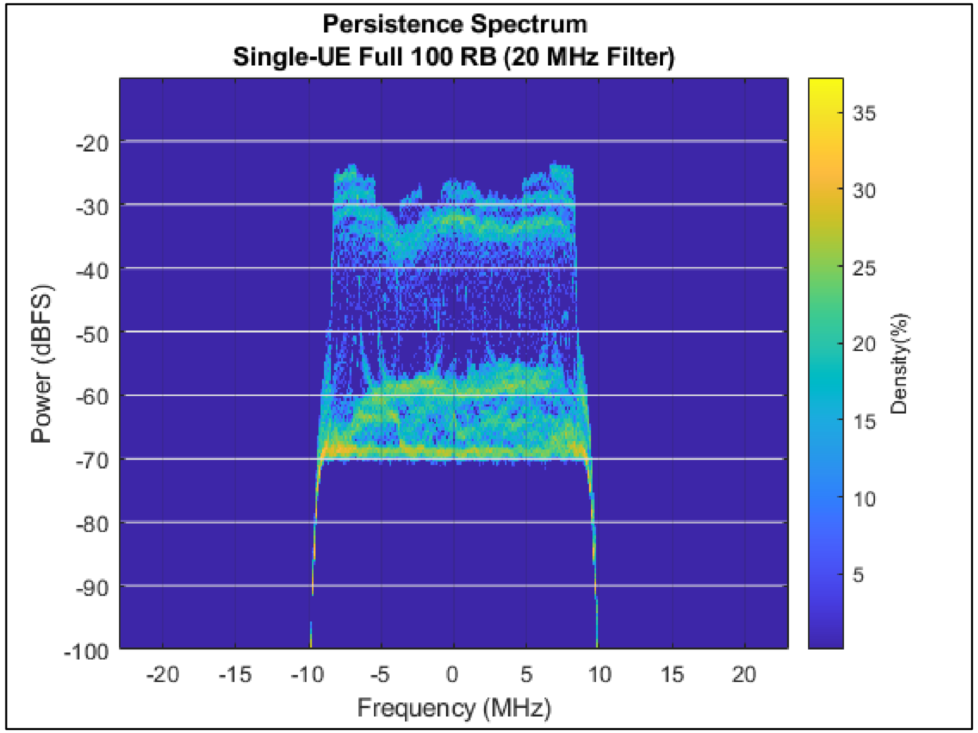
Frequency Offset Experiments

- ABE level set to as captured in the field
- ABE waveforms include OOBE
- ABE waveforms with extended noise floor

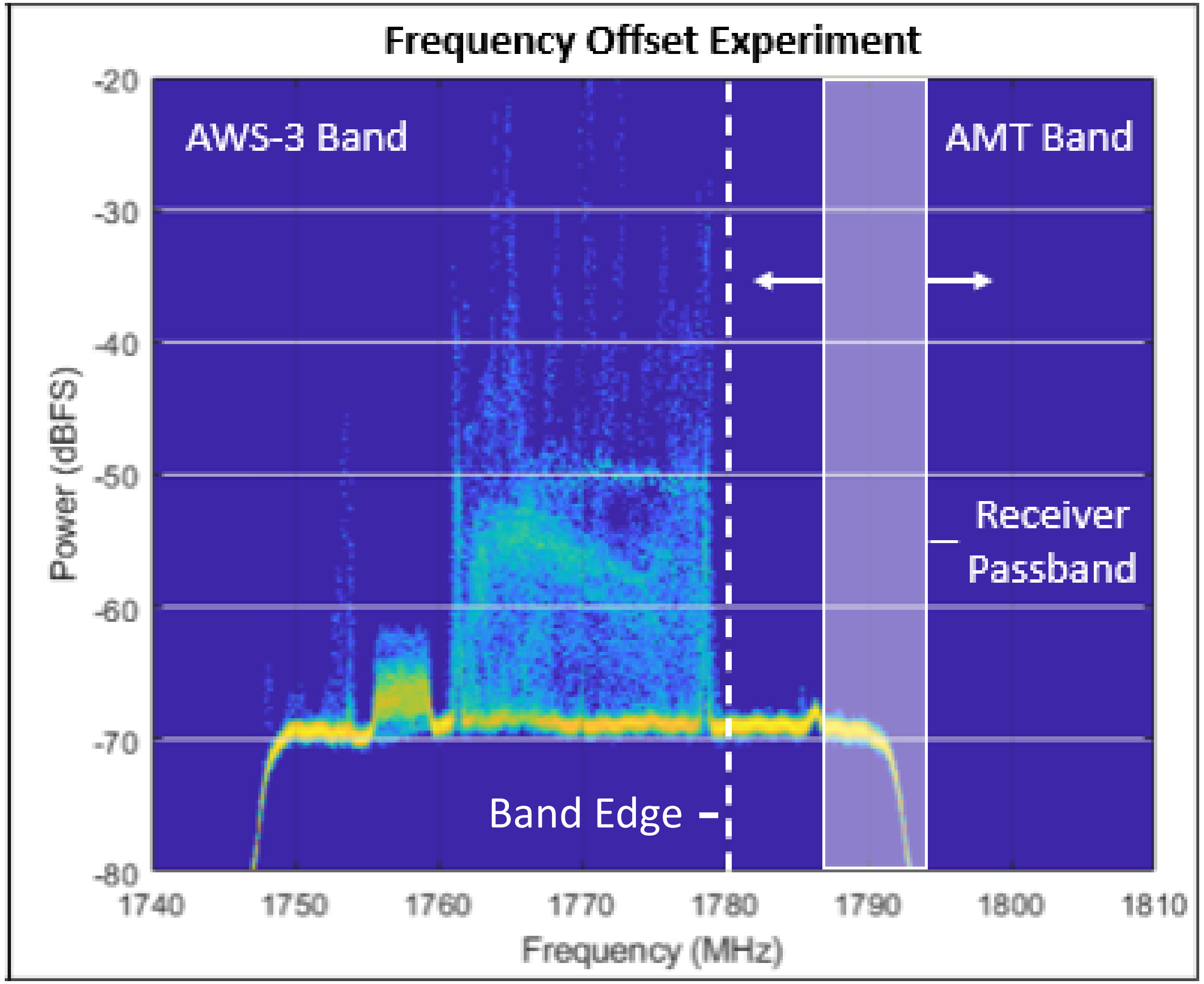


Band Edge and N_a^{eff} Experiments

- ABE level target same peak level
- ABE waveforms filtered to 20 MHz in-band occupied bandwidth
- Adjacent band testing of LTE fundamental



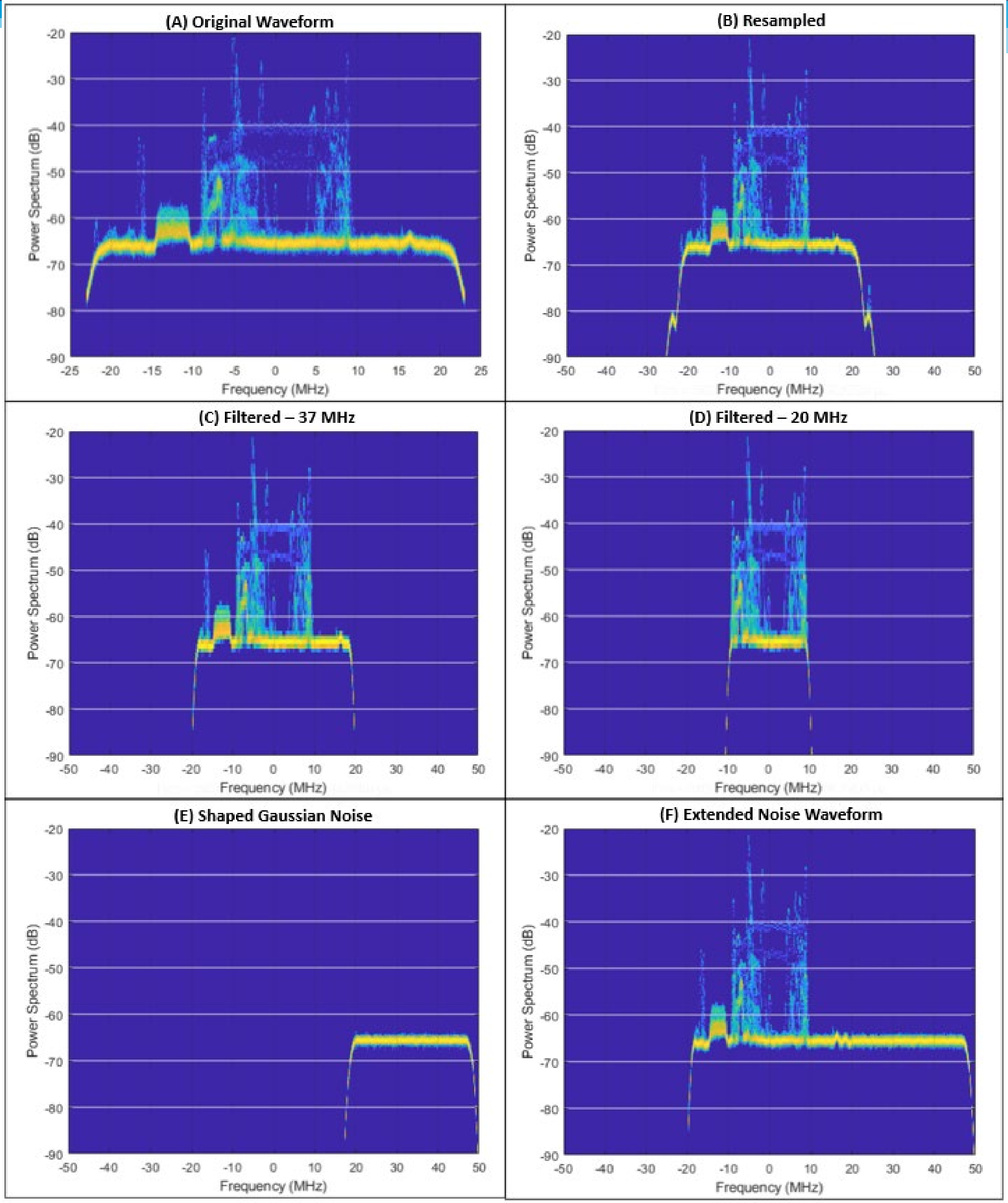
ABE Waveform processing for Frequency offset Experiments



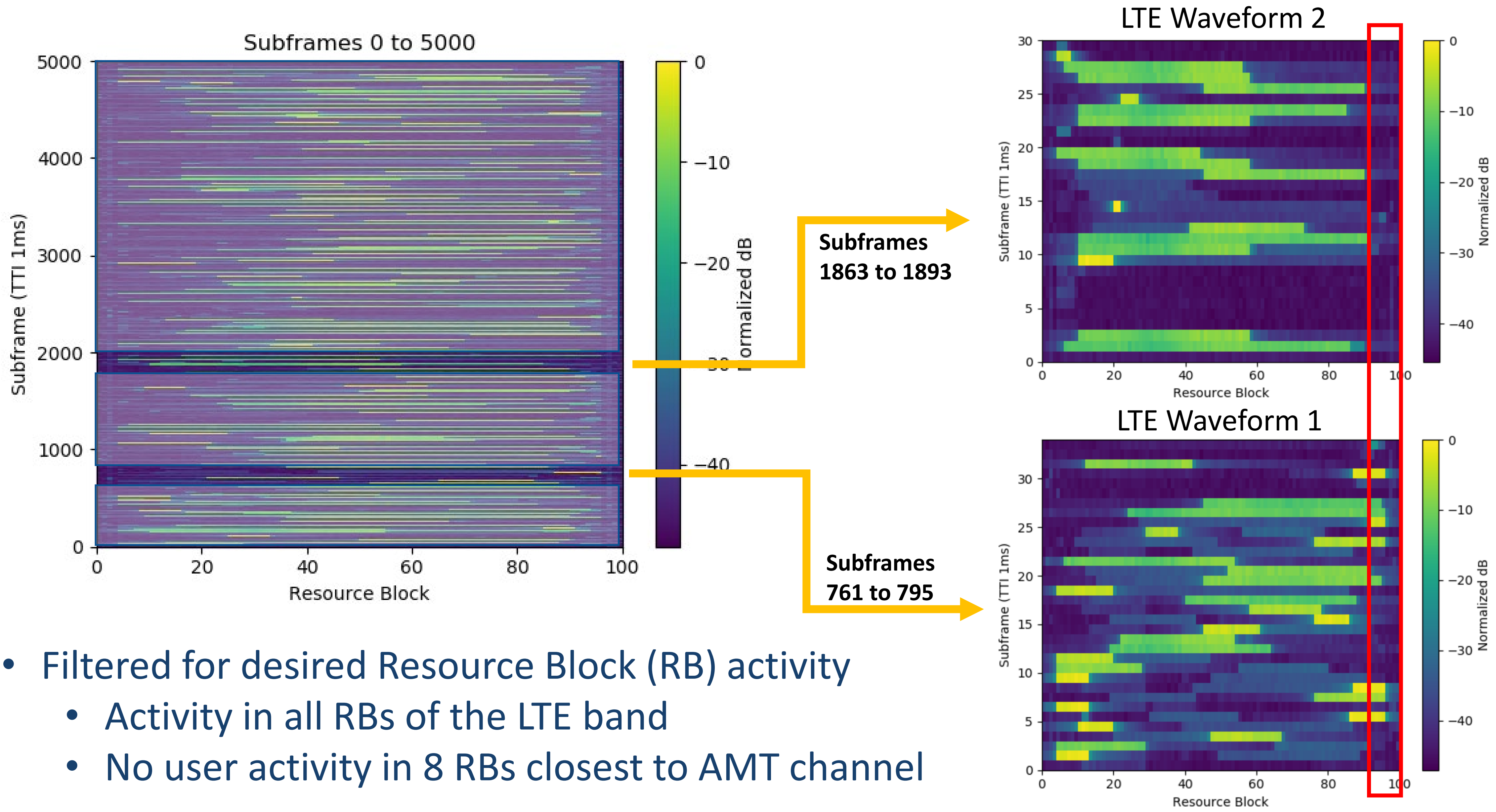
- Receiver Passband can overlap with as captured VSA roll off and is dependent on:
  - IF Filter Selection by the receiver
  - IRIG Band Edge back off frequency
  - Frequency range of the experiment
- To mitigate we present an approach to extend the noise floor of the waveforms

Noise “Floor” Extension Process

- Resample Original waveform
- Apply a bandpass filter (based on VSA calibration window) to the resampled waveform
- Develop an AWGN signal at the same level as the noise shoulder of the original waveform
- Combine the signals



In-Situ Single UE from Edwards – LTE Waveforms



- Filtered for desired Resource Block (RB) activity
  - Activity in all RBs of the LTE band
  - No user activity in 8 RBs closest to AMT channel

Frequency Offset Experiment: IRIG-based Analysis

Frequency Offset Experiment

Objective: Characterize effect of shifting AMT center frequency relative to ABE

Id	Factor	Settings	# Levels	Easy/Hard to Change
A	Modulation Type	PCM/FM, SOQPSK, SOQPSK-FEC, ARTM-CPM	4	Hard
B	Bit Rate	1, 5, 10 Mbps	4	Hard
C	ABE Type	AWGN 20 MHz, in-situ LTE captures: single-UE (92 RB, Full, 92 RB filtered, Full filtered), multi-UE: (EAFB Az76, EAFB Az198), lab LTE captures (20 MHz Full, 20 MHz upper 10 RB blanked, 5 MHz Full)	10	Hard
D	Frequency Offset	1 MHz steps on grid including IRIG-recommended offset	12	Hard

- Only test Modulation/Bit Rate combinations shown in yellow
- Same S_{ave}/ABE_{peak} ratio for each LTE waveform
- S_{ave}/ABE_{ave} fixed for AWGN
- 840 unique test configurations
- Repeats/replication
  - All configurations tested twice at MITRE-Bedford
  - Subset tested twice at NIST-Boulder (excluding SOQPSK-FEC)

Modulation Type	Bit Rate (Mbps)			
PCM/FM	1	5		
SOQPSK		5	10	
SOQPSK- FEC		5	10	
ARTM CPM		5		

IRIG 106 Band Edge Back Off

- Determined by:
  - Transmitter power output
  - Power spectral density masks
  - Modulation
  - Bit rate
  - Channelization frequency discretization

AMT Transmitter center frequency spacing to the band edge

Modulation / Bit Rate	PCM/FM	SOQPSK	SOQPSK FEC*	ARTM CPM
1 Mbps	2.5 MHz	Not Tested	Not Tested	Not Tested
5 Mbps	10.0 MHz	5.0 MHz	7.5 MHz	4.0 MHz
10 Mbps	Not Tested	9.0 MHz	14.0 MHz	Not Tested

Test configurations shown in yellow

*LDPC Code Rate 2/3 Information Block Size 4096

- Calculations based on 10W transmitter
- Band Edge frequency: 1780 MHz

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Inter-Range Instrumentation Group: Range Commanders Council Telemetry Group.
IRIG 106-19: Telemetry Standards.
Section A.12: Valid Center Frequencies Near Telemetry Band Edges

AMT Signal and ABE Waveform Levels

Configure the testbed AMT Signal pathloss and ABE pathloss such that at the N-type connector of the receiver:

- AMT average signal targeted -80 dBm
- ABE peak value of in-situ waveforms = ABE peak value as recorded in the field
- ABE peak value of Lab waveforms targeted in-situ single UE ABE peak value
- AWGN 20 MHz average signal targeted Single UE Full 100 RB (37 MHz Filter) average signal

AMT Signal and ABE Levels for Frequency Offset Experiment

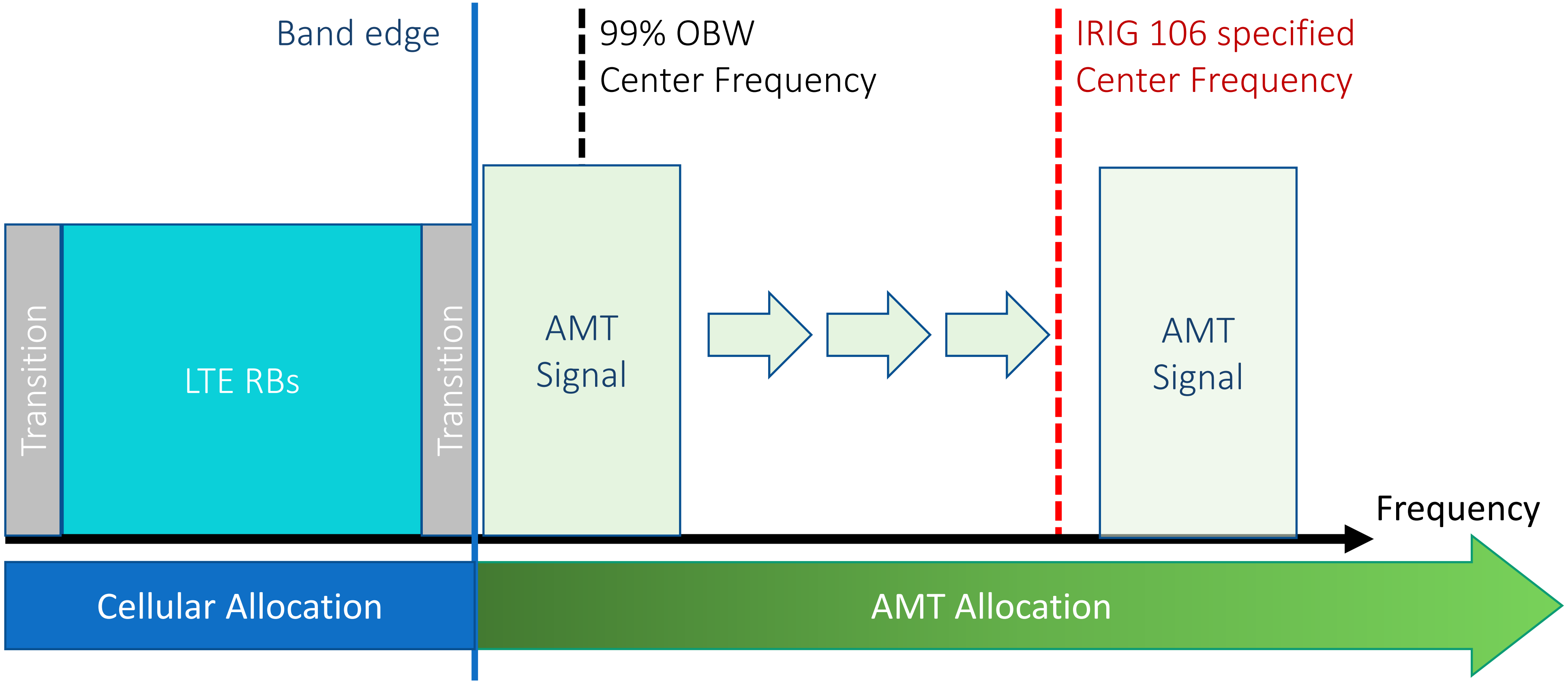
Test Case	AMT Signal Average (dBm)
Frequency Offset Experiments	-79.9 ± 0.9 dB

Waveform	Average (dBm)	Peak (dBm)
AWGN 20 MHz	-59.6 ± 1.1 dB	N/A
Single UE Full 100 RB (20 MHz Filter)	-63.4 ± 1.1 dB	-52.2 ± 1.1 dB
Single UE Lower 92 RB (20 MHz Filter)	-63.5 ± 1.1 dB	-52.7 ± 1.1 dB
Single UE Full 100 RB (37 MHz Filter)	-60.5 ± 1.1 dB	-52.4 ± 1.1 dB
Single UE Lower 92 RB (37 MHz Filter)	-63.4 ± 1.1 dB	-52.8 ± 1.1 dB
Multi-UE Az-76 100 RB (EAFB 37 MHz Filter)	-70.6 ± 1.1 dB	-48.0 ± 1.1 dB
Multi-UE Az-198 100 RB (EAFB 37 MHz Filter)	-82.5 ± 1.1 dB	-53.9 ± 1.1 dB
Lab-UE Full 100 RB (49 MHz Filter)	-66.0 ± 1.1 dB	-52.9 ± 1.1 dB
Lab-UE Lower 90 RB (49 MHz Filter)	-65.4 ± 1.1 dB	-52.9 ± 1.1 dB
Lab-UE Full 25 RB (49 MHz Filter)	-70.7 ± 1.1 dB	-52.9 ± 1.1 dB

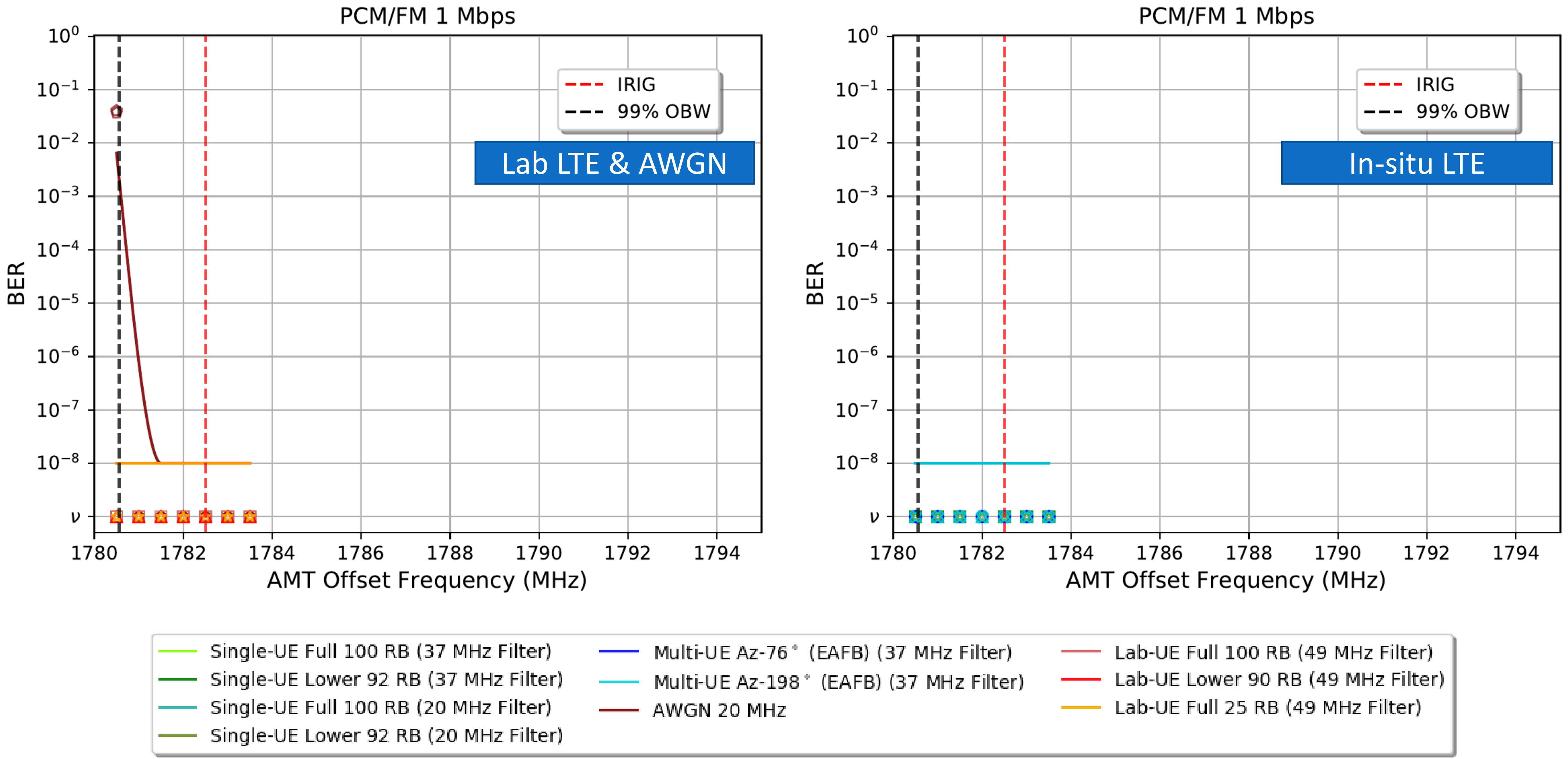
Uncertainties are expanded uncertainties for the MITRE Bedford testbed as calculated in Appendix A of the Report

Frequency Offset Experiment Procedure

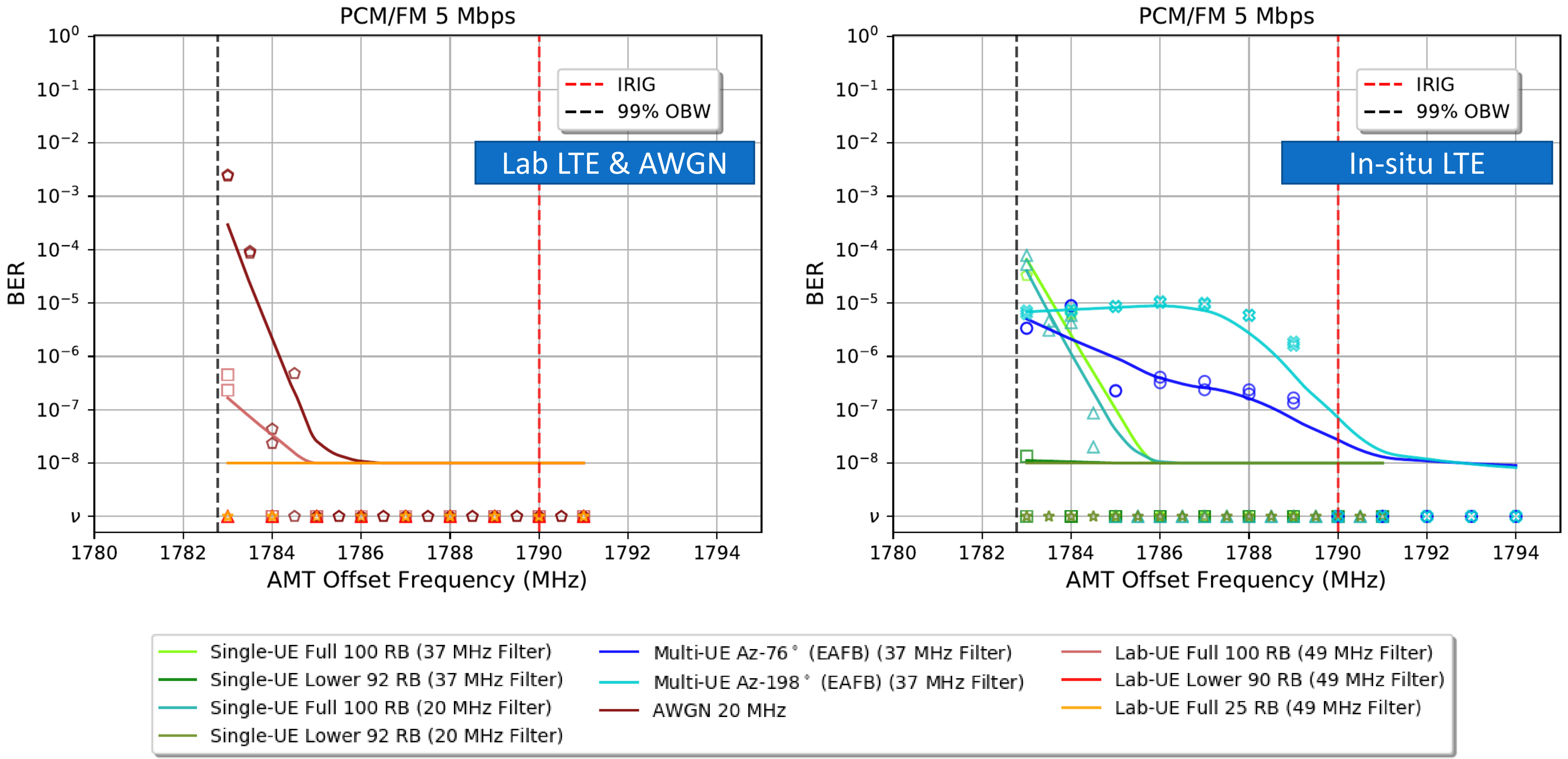
- AMT signal frequency is varied across the range from near band edge beyond IRIG 106



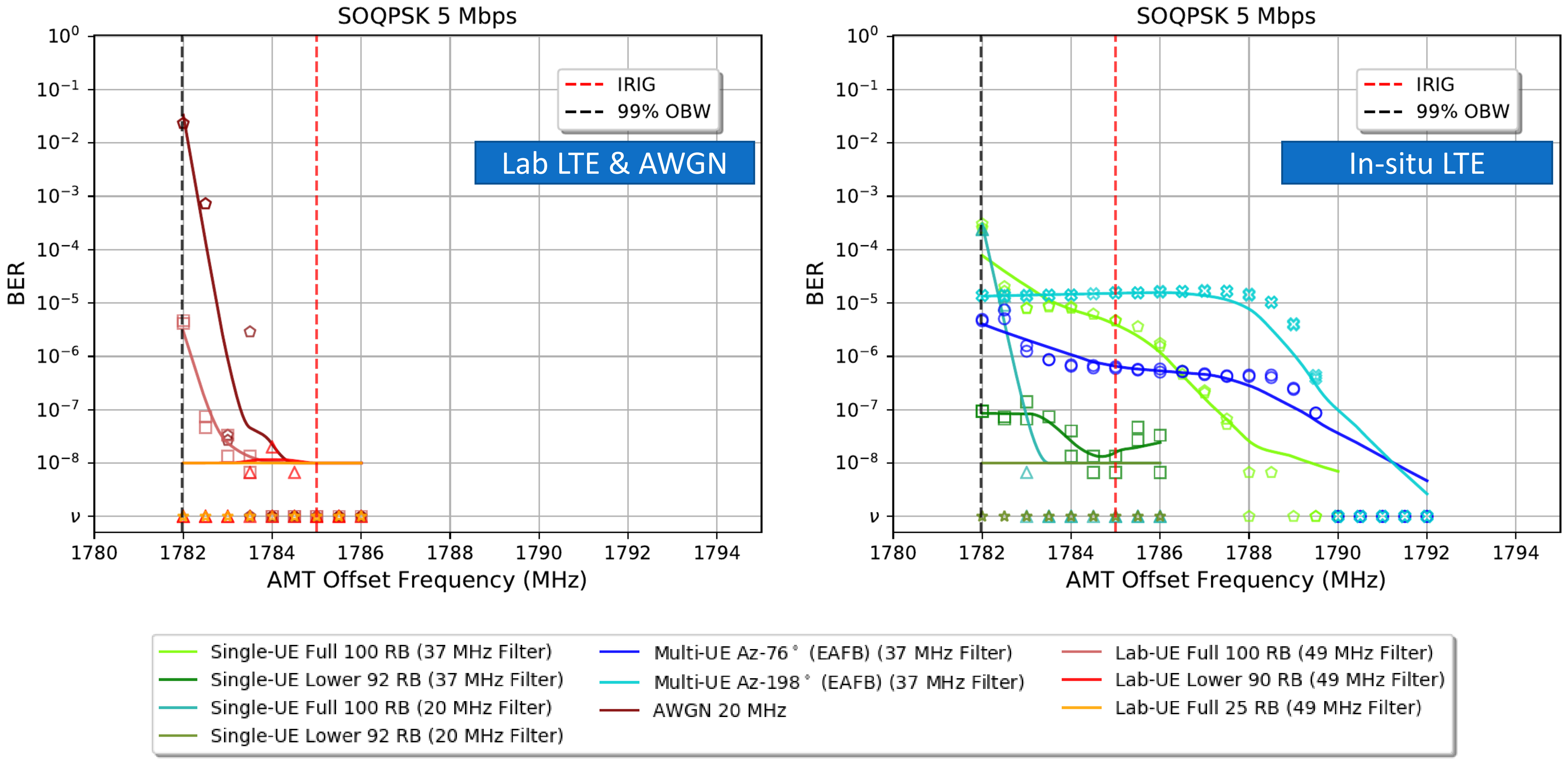
Frequency Offset Results: PCM/FM 1 Mbps



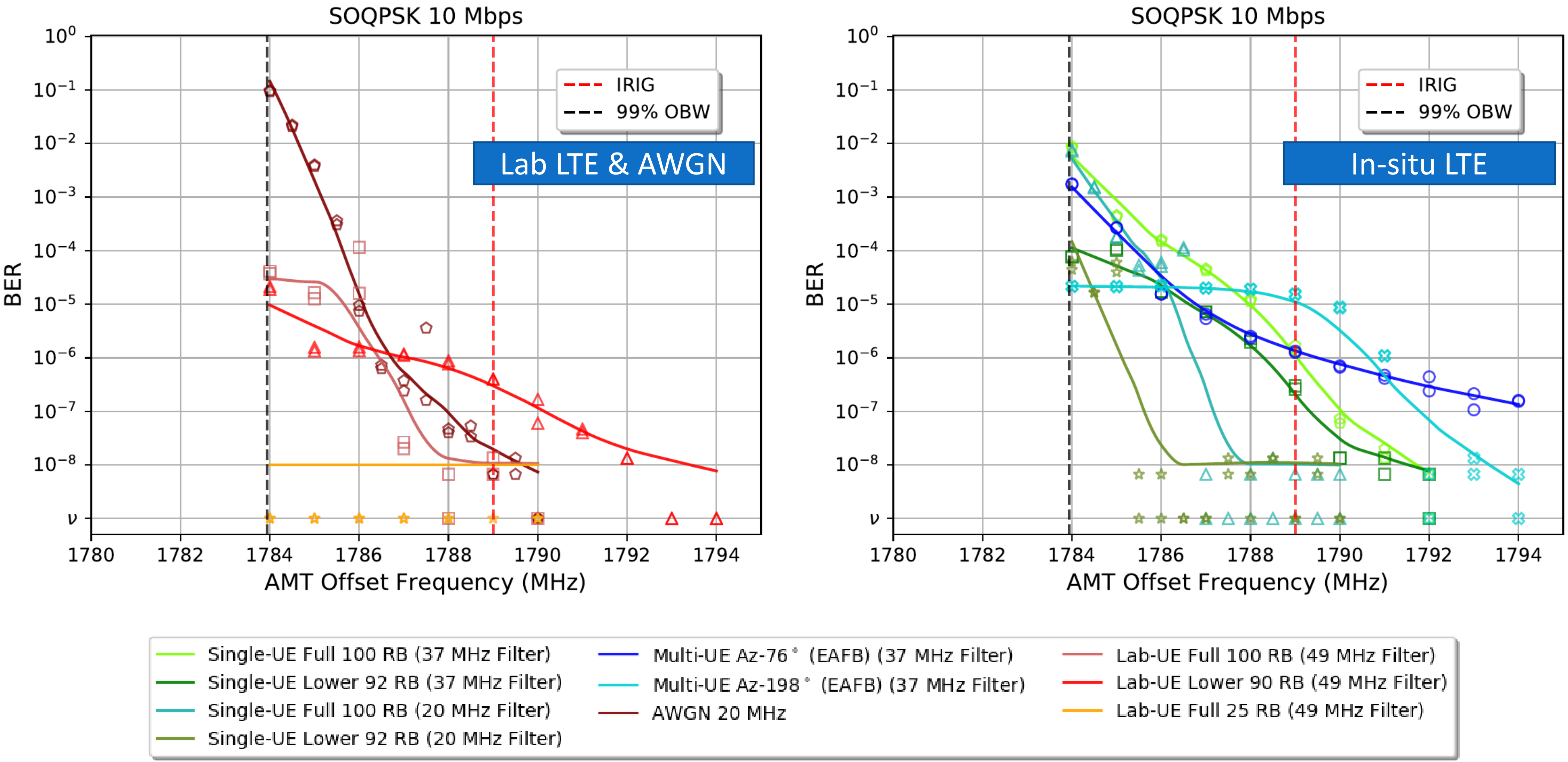
Frequency Offset Results: PCM/FM 5 Mbps



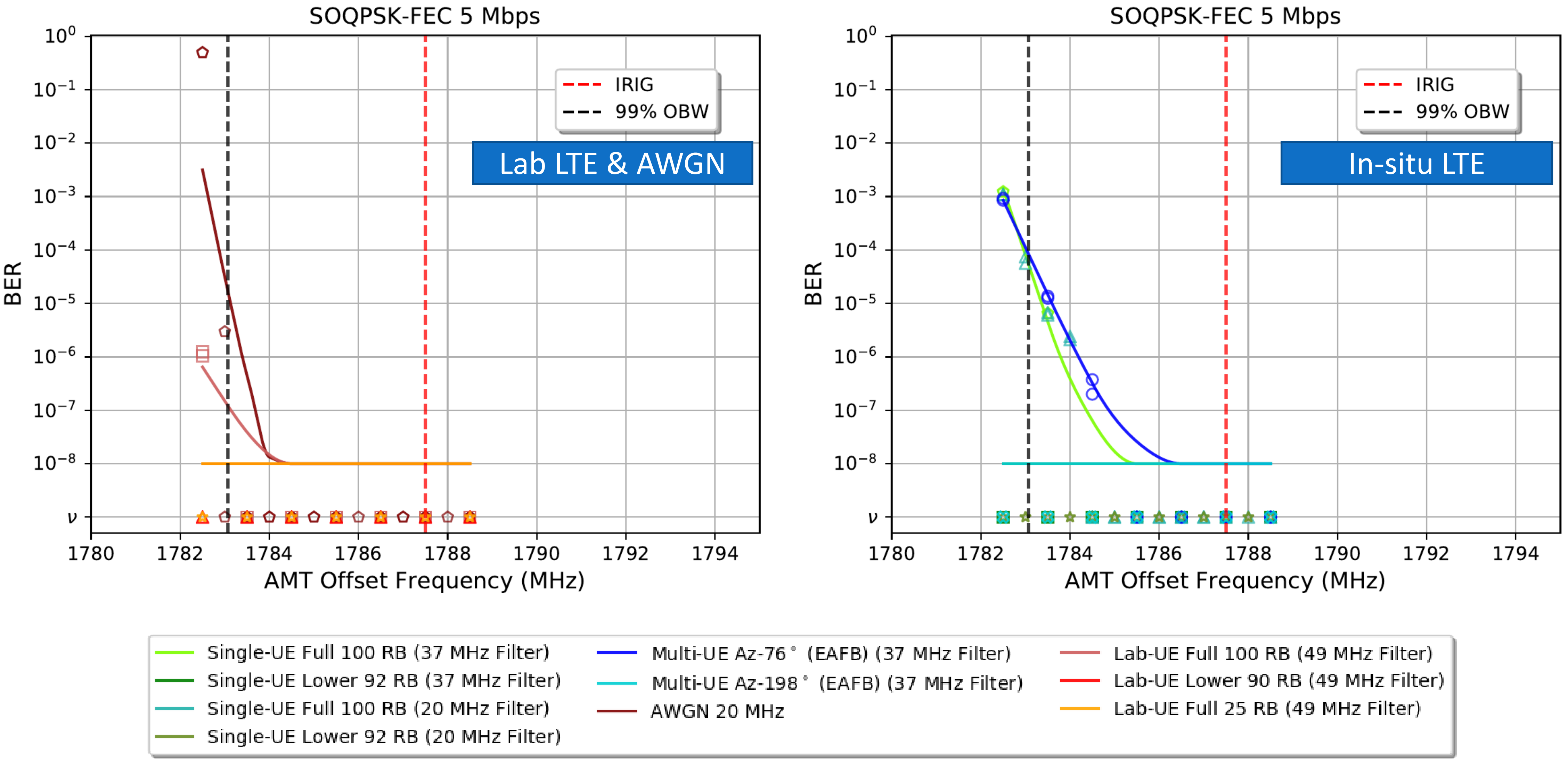
Frequency Offset Results: SOQPSK 5Mbps



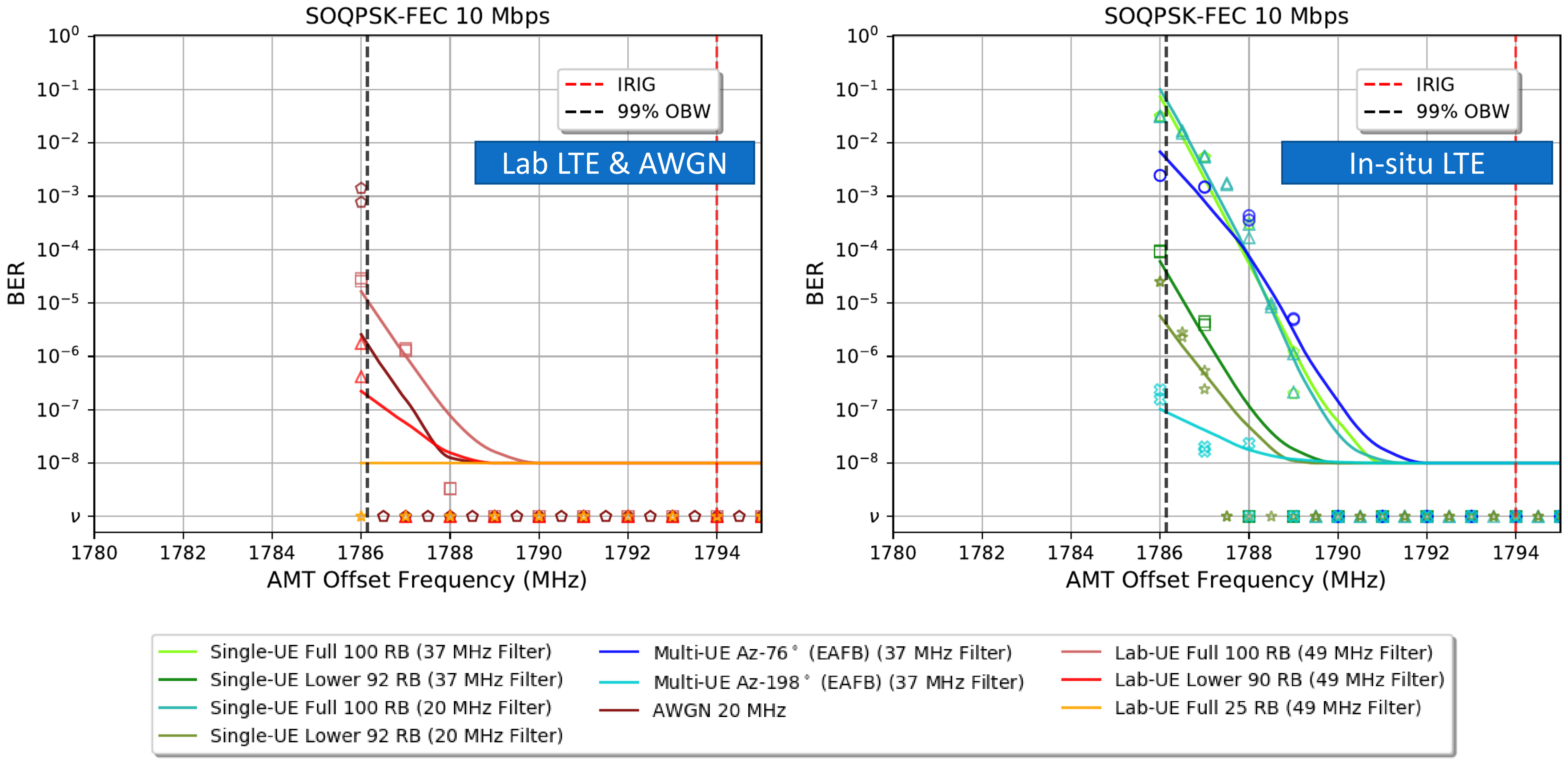
Frequency Offset Results: SOQPSK 10 Mbps



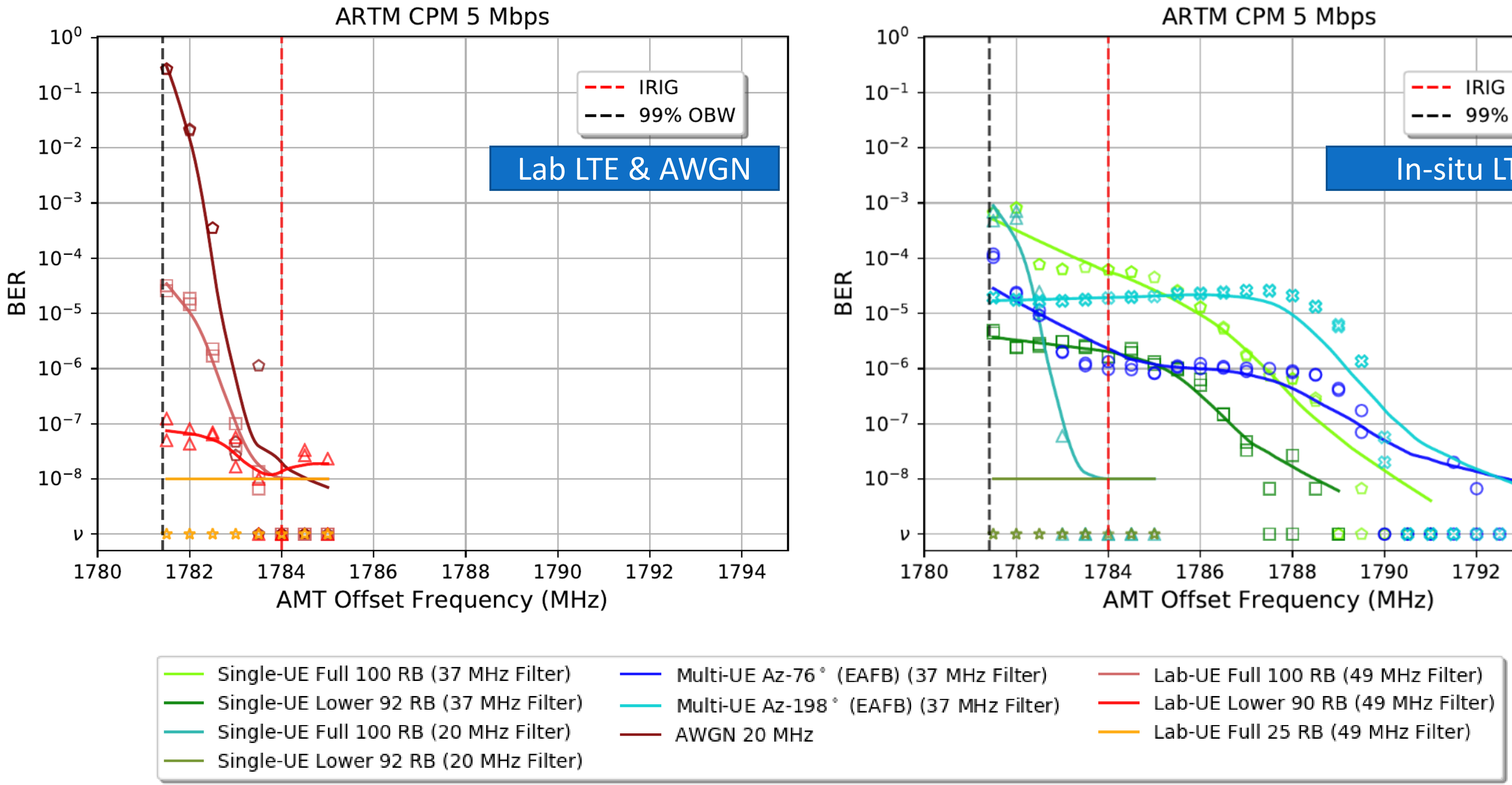
Frequency Offset Results: SOQPSK FEC 5 Mbps



Frequency Offset Results: SOQPSK-FEC 10 Mbps



Frequency Offset Results: ARTM CPM 5 Mbps



Selected Results from Main Characterization Experiment

Main Characterization Experiment

Objective: Assess impact of different ABE types on AMT receiver performance. Cover transition from strong link (BER < 10^{-7}) to a poor link (BER > 10^{-4})

Id	Factor	Settings	# Levels	Easy/Hard to Change
A	Modulation Type	PCM/FM, SOQPSK, SOQPSK-FEC, ARTM-CPM	4	Hard
B	Bit Rate	1, 5, 10, 20 Mbps	4	Hard
C	ABE Type	None, AWGN (BW=20, 18, 16.5 MHz), in-situ LTE captures: single-UE (92 RB, Full), multi-UE (EAFB Az76, EAFB Az198, LaRC Az140, LaRC Az165)	10	Hard
D	AMT Signal Level	1 dB steps on grid spanning a 10 dB range with config-dependent shift	11	Easy

- Configurations not tested:
  - PCM/FM at 20 Mbps, ARTM-CPM at 1 Mbps
- 1540 unique test configurations
- Repeats/replication
  - All configurations tested twice at MITRE-Bedford
  - Subset tested twice at NIST-Boulder (excluding SOQPSK-FEC)

Showcased

Modulation Type	Bit Rate (Mbps)			
PCM/FM	1	5	10	
SOQPSK	1	5	10	20
SOQPSK- FEC	1	5	10	20
ARTM CPM		5	10	20

First priority shown in yellow

ABE Levels as Tested at Band Edge

Waveform	Frequency Offset: Average (dBm)	Frequency Offset: Peak (dBm)
AWGN 20 MHz	-75.8 ± 0.9 dB	N/A
AWGN 18 MHz	-76.4 ± 0.9 dB	N/A
AWGN 16.5 MHz	-76.8 ± 0.9 dB	N/A
Single UE Full 100 RB (20 MHz Filter)	-69.9 ± 1.1 dB	-61.8 ± 1.1 dB
Single UE Lower 92 RB (20 MHz Filter)	-72.8 ± 1.1 dB	-62.3 ± 1.1 dB
Multi-UE Az-76 100 RB (EAFB 20 MHz Filter)	-84.6 ± 1.1 dB	-62.1 ± 1.1 dB
Multi-UE Az-198 100 RB (EAFB 20 MHz Filter)	-86.5 ± 1.1 dB	-62.1 ± 1.1 dB
Multi-UE Az-140 100 RB (LaRC 20 MHz Filter)	-80.3 ± 1.1 dB	-62.1 ± 1.1 dB
Multi-UE Az-165 100 RB (LaRC 20 MHz Filter)	-78.9 ± 1.1 dB	-62.1 ± 1.1 dB

Tests aligned to consistent PSD

Tests aligned to Peak Power

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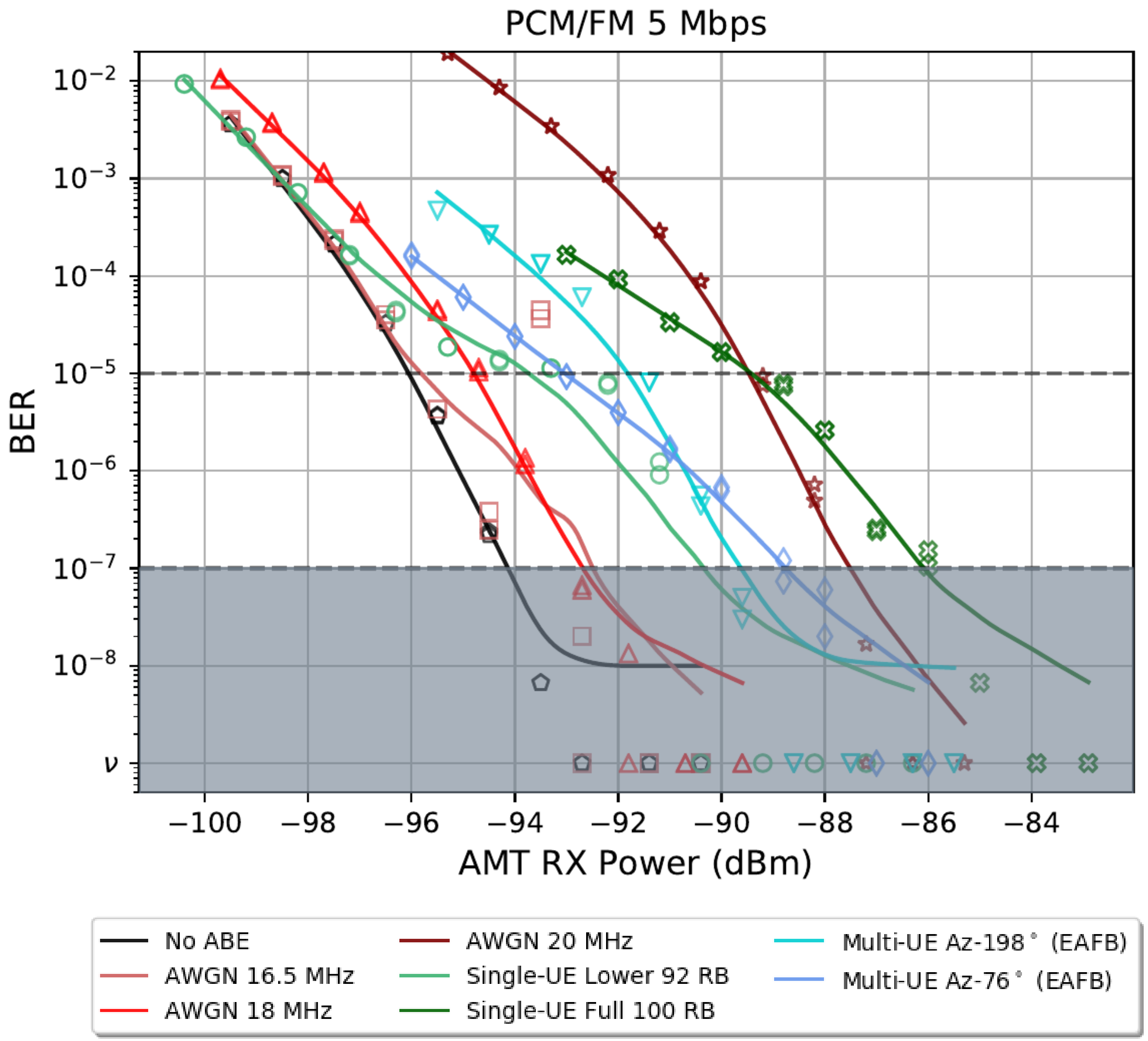
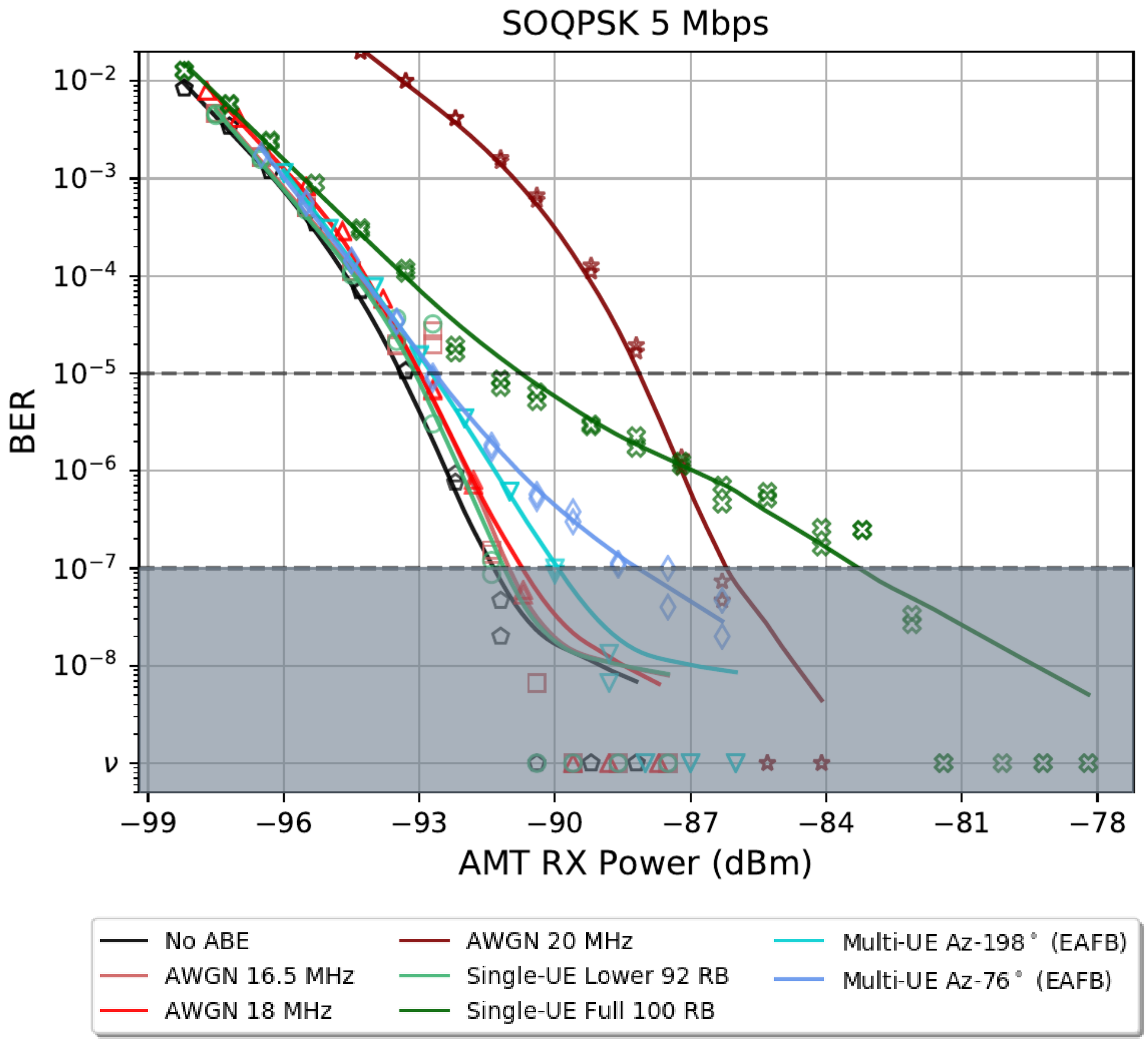
Uncertainties are expanded uncertainties for the MITRE Bedford testbed as calculated in Appendix A of the Report

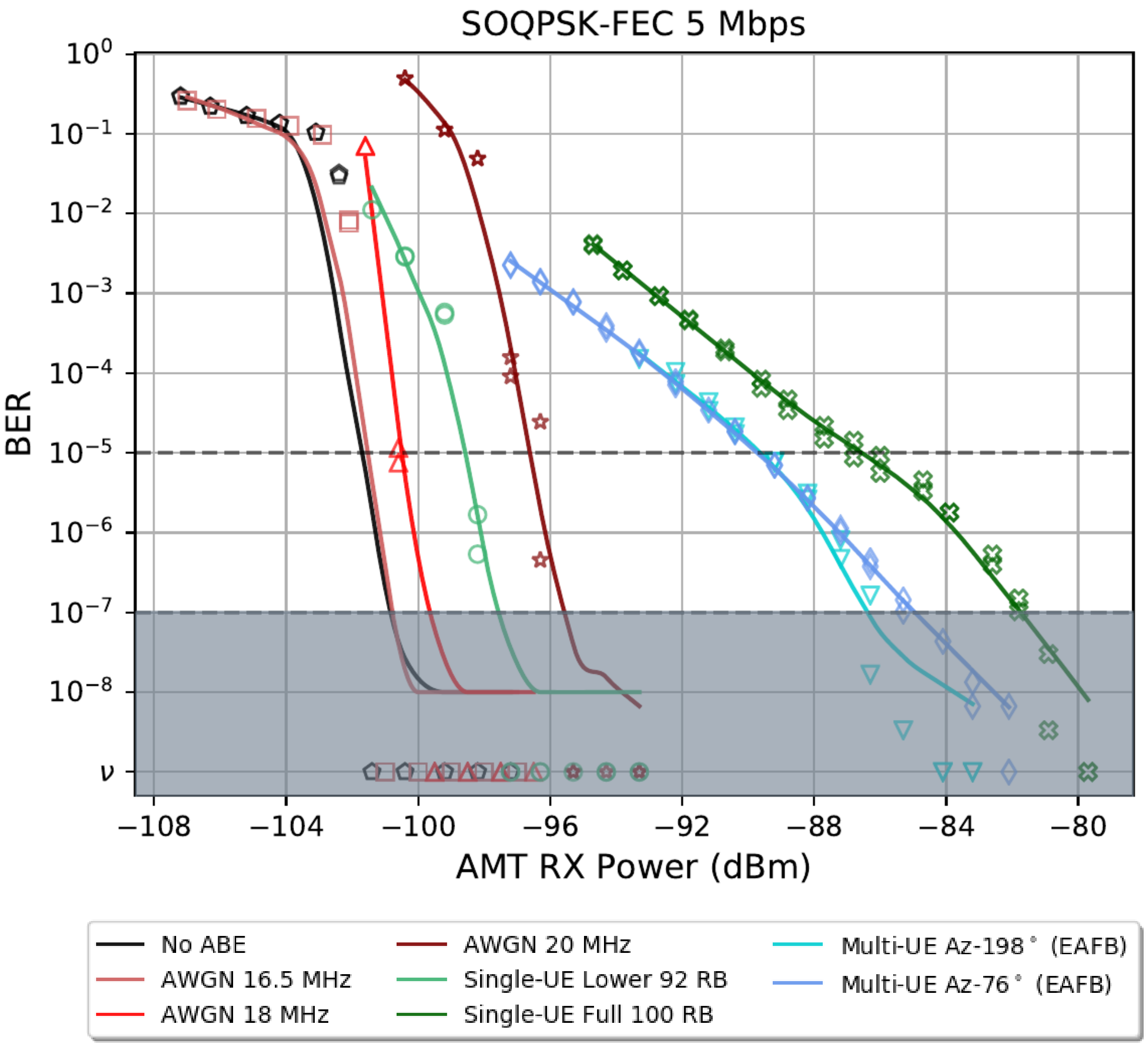
Main Experiment: PCM/FM 5 Mbps



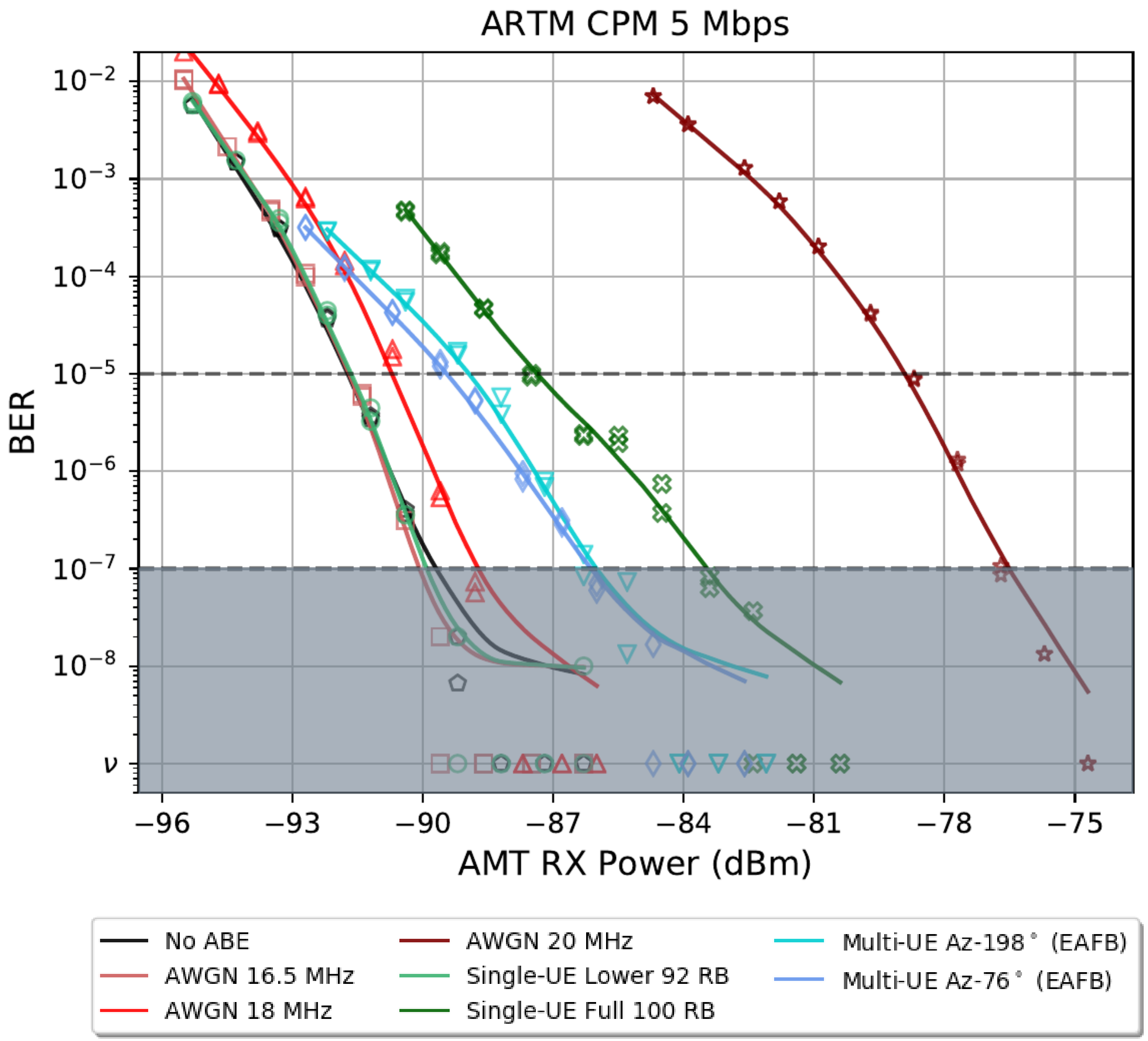
Main Experiment: SOQPSK 5 Mbps



Main Experiment: SOQPSK-FEC 5 Mbps

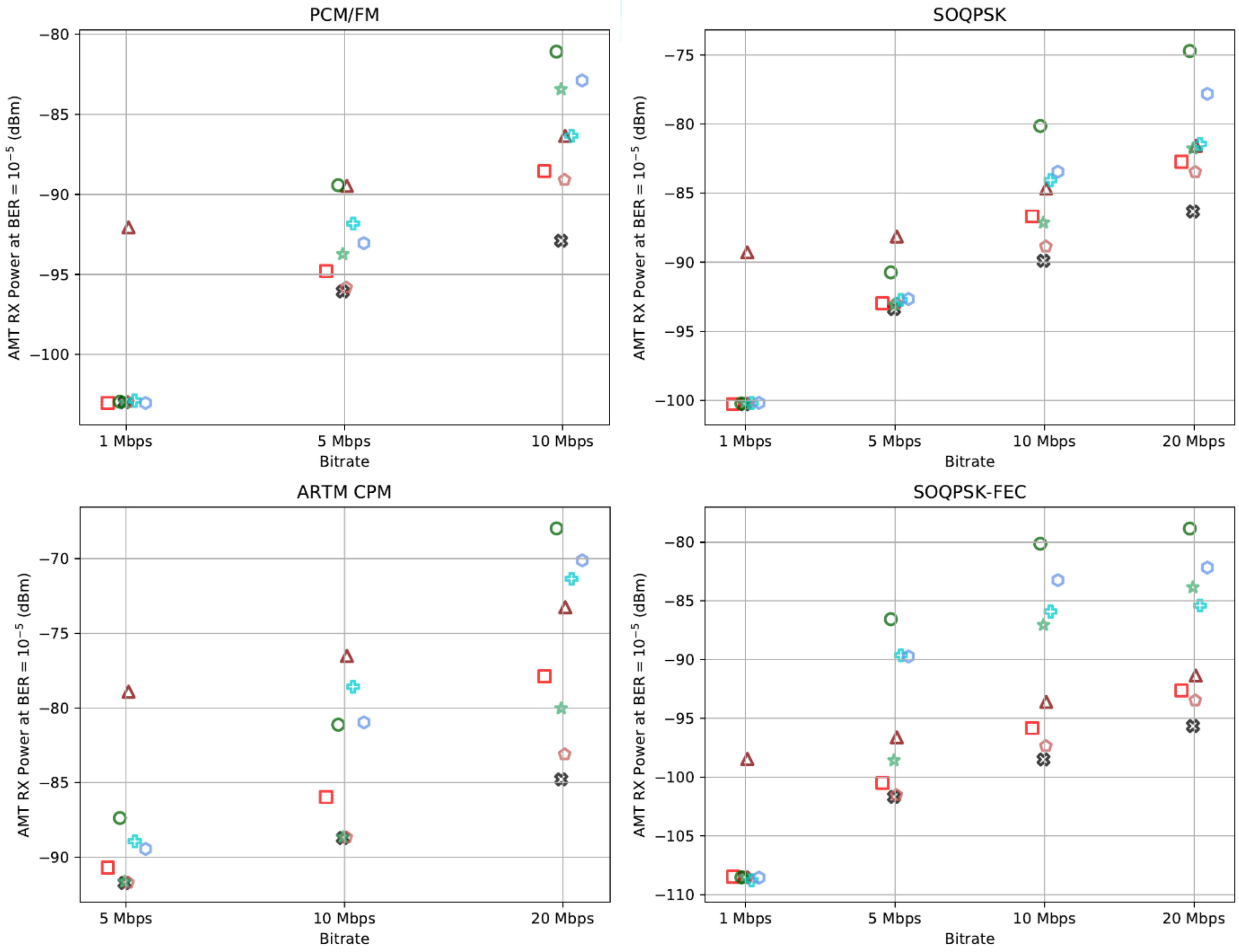


Main Experiment: ARTM CPM 5 Mbps



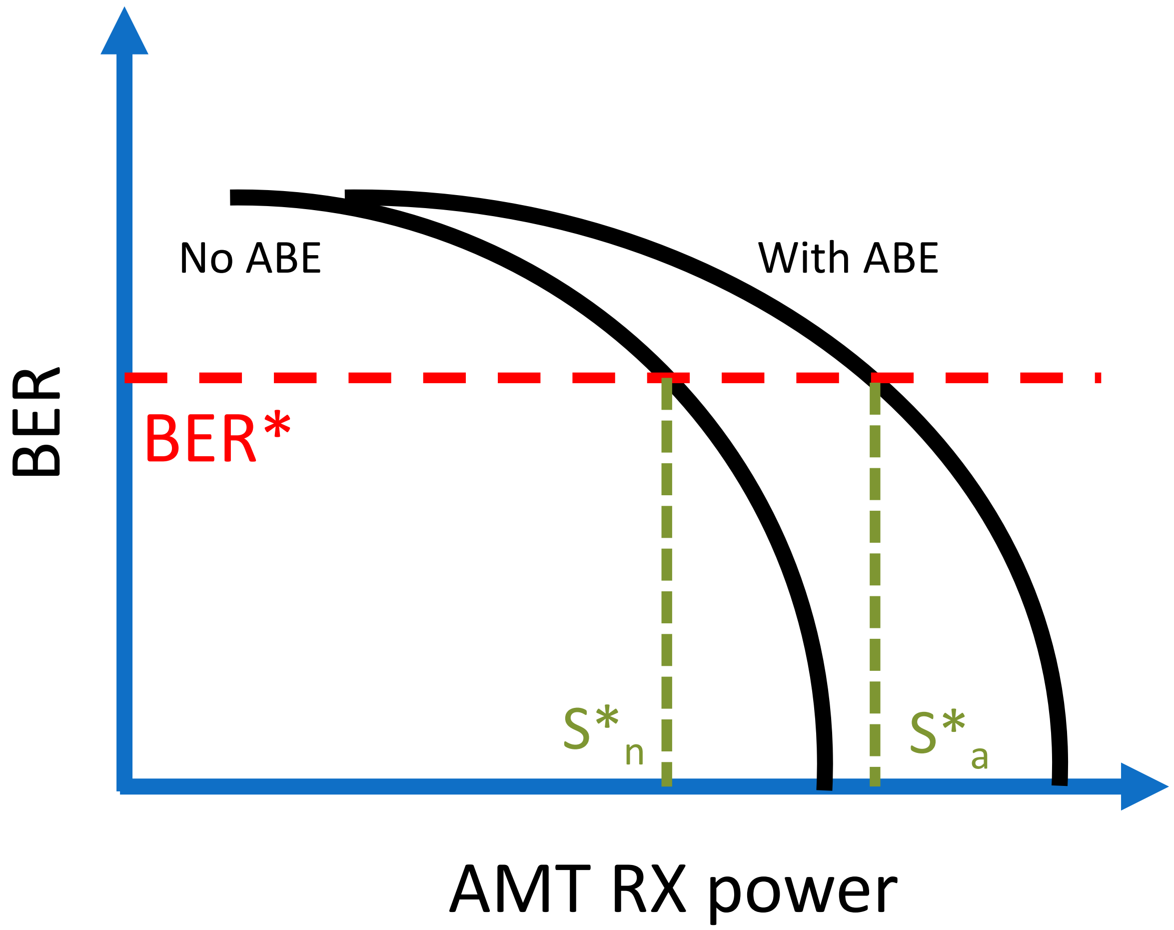
Summary of BER =10^{-5} Behaviors

- No ABE
- AWGN 16.5 MHz
- AWGN 18 MHz
- AWGN 20 MHz
- Single-UE Lower 92 RB
- Single-UE Full 100 RB
- Multi-UE Az-198° (EAFB)
- Multi-UE Az-76° (EAFB)



Equivalent Ambient Noise (Eb/N0 Loss) Analysis

Can we characterize the impact of adjacent band emissions in terms of an equivalent ambient noise level?



1) At a fixed BER = BER*, set

$$E_b/N_o \big|_{\text{no ABE}} = E_b/N_a^{eff} \big|_{\text{ABE}}$$

- In other words, define N_a^{eff} as the equivalent noise power density that yields the same BER as in the no-ABE case.

2) Letting S^*_n and S^*_a denote the signal power at BER* for the no-ABE and ABE cases, and using E_b = S/BR, yields

$$N_a^{eff} = N_o(S^*_a / S^*_n)$$

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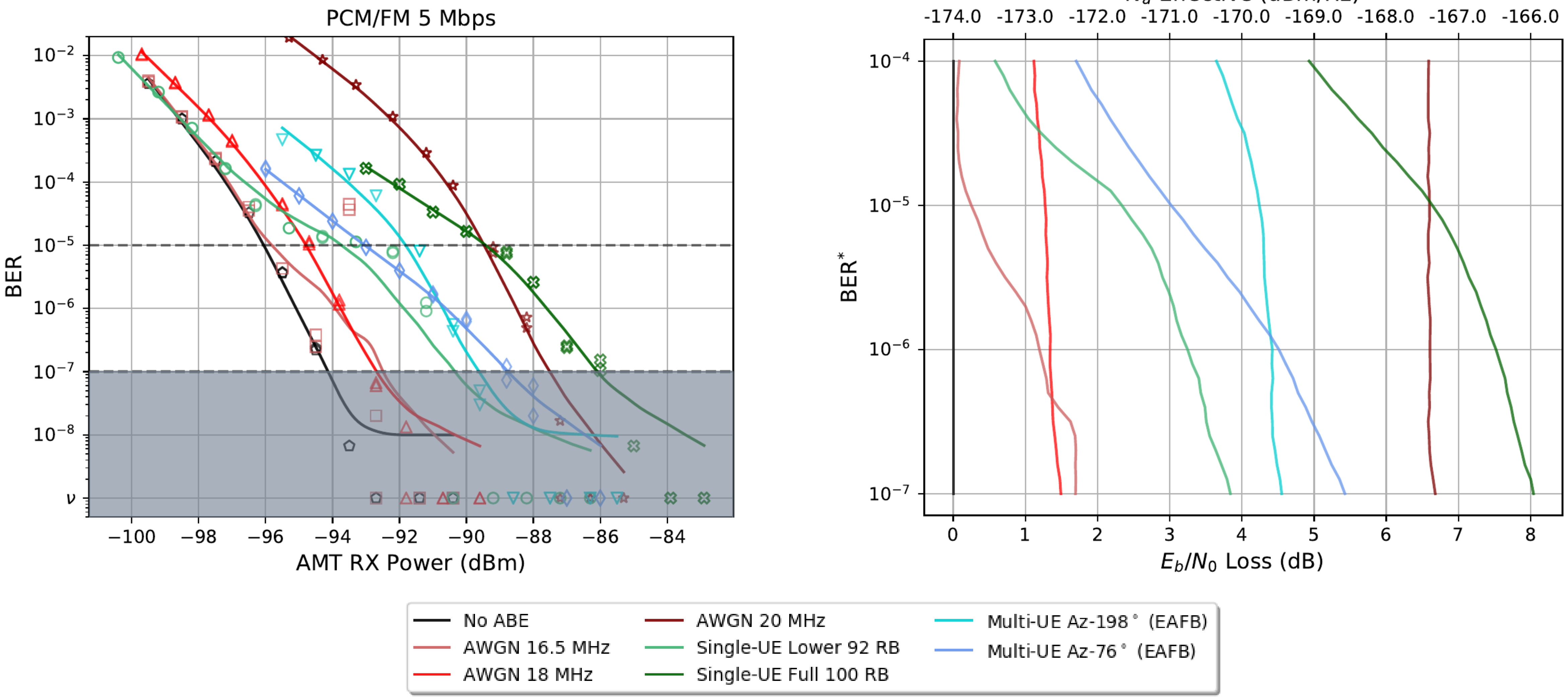
Main Experiment: PCM/FM 5 Mbps

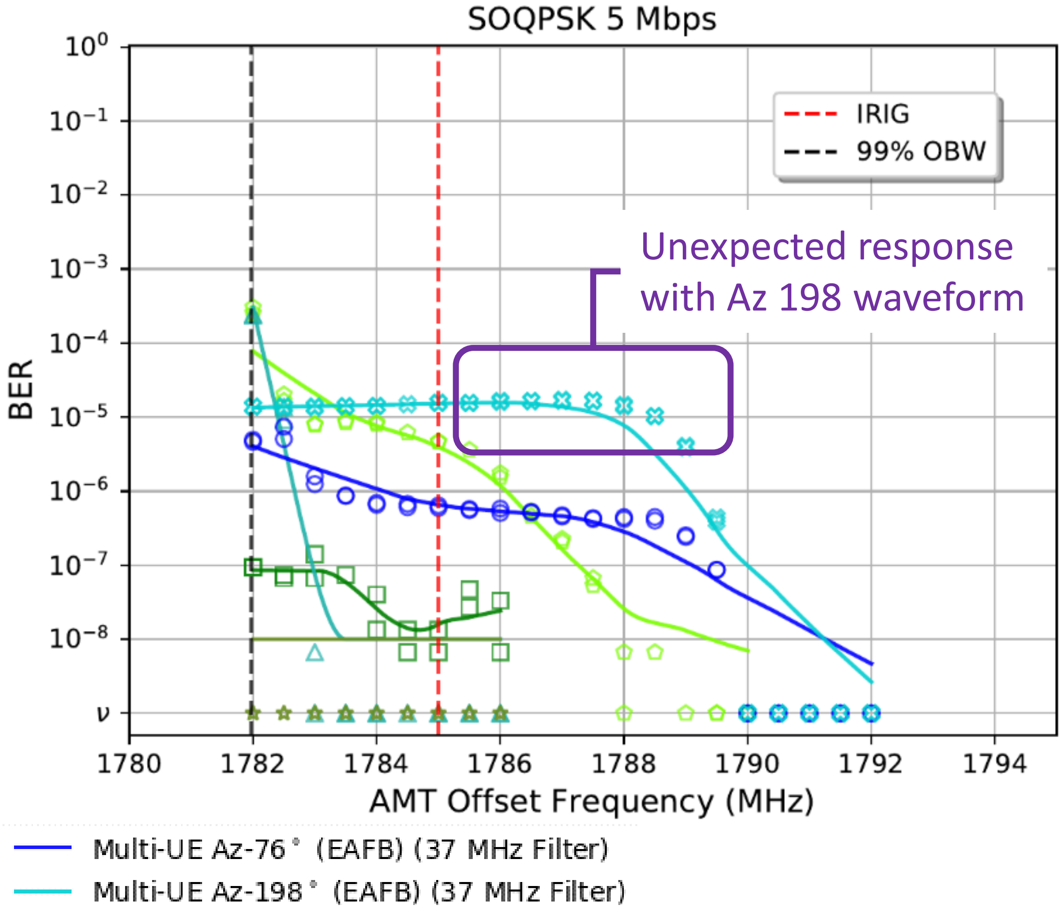
BER vs AMT Rx Power

BER* vs N_a effective

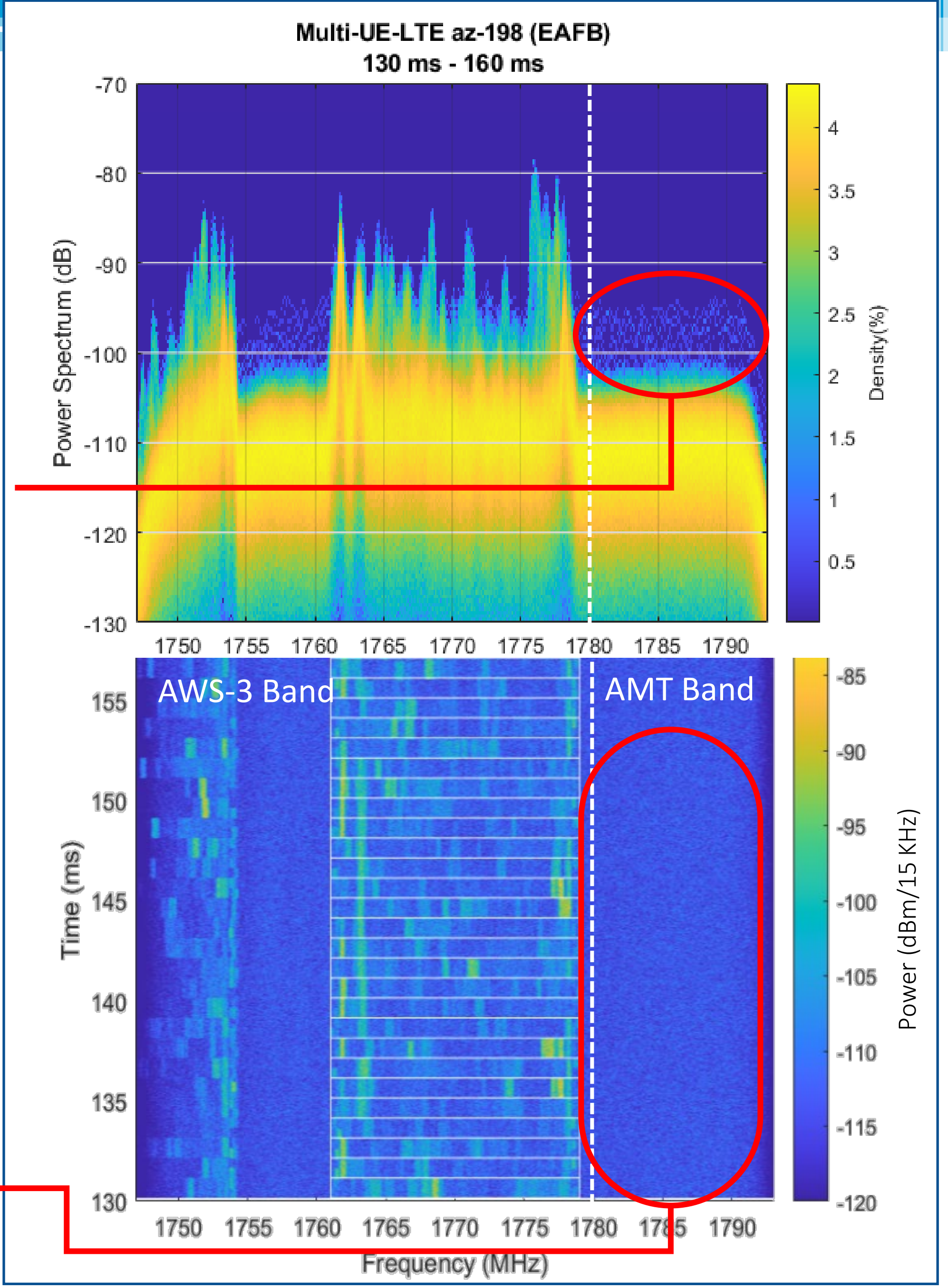


Anomalous Results

Anomalous Result –
Frequency Offset Experiment: Az 198 Waveform

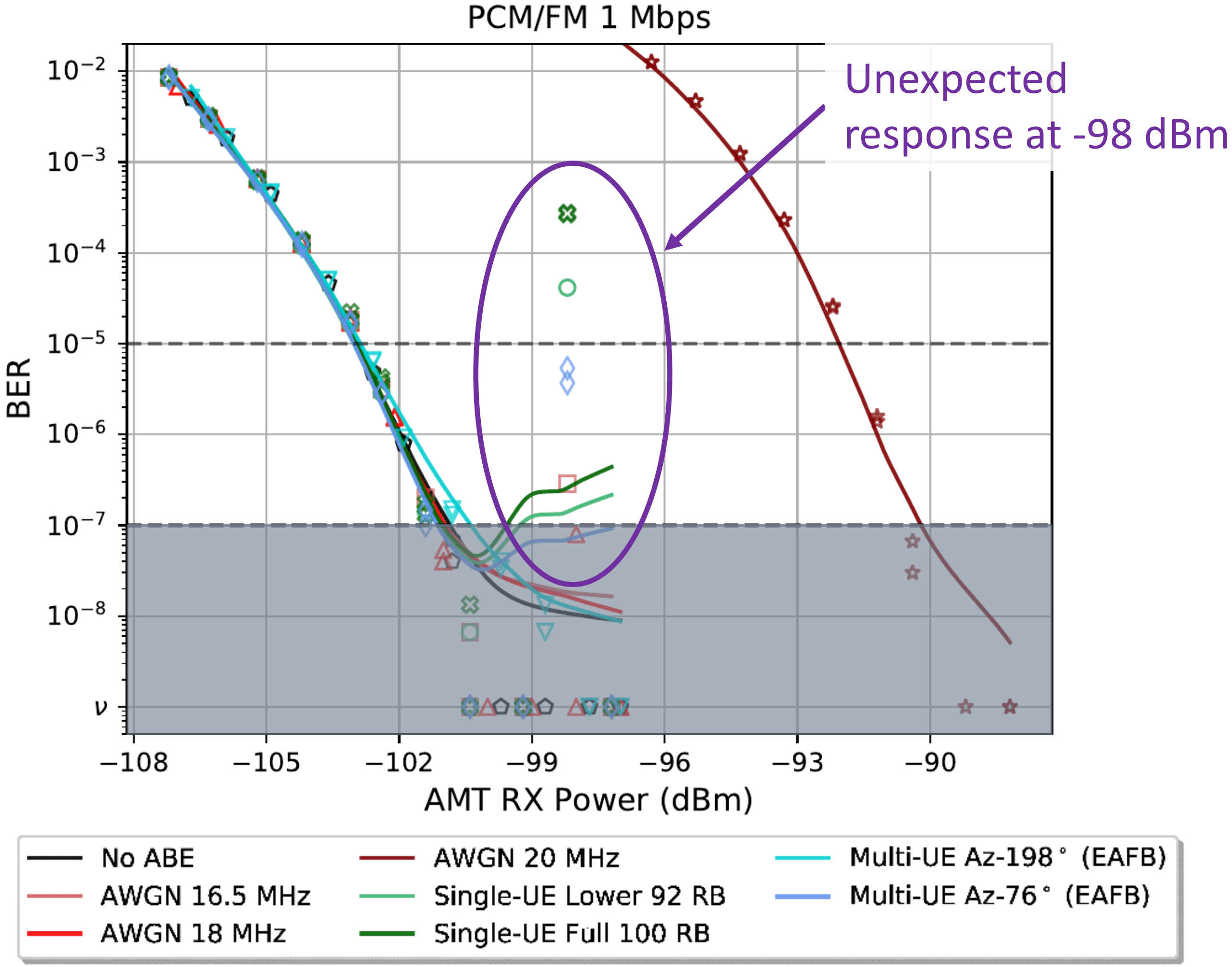


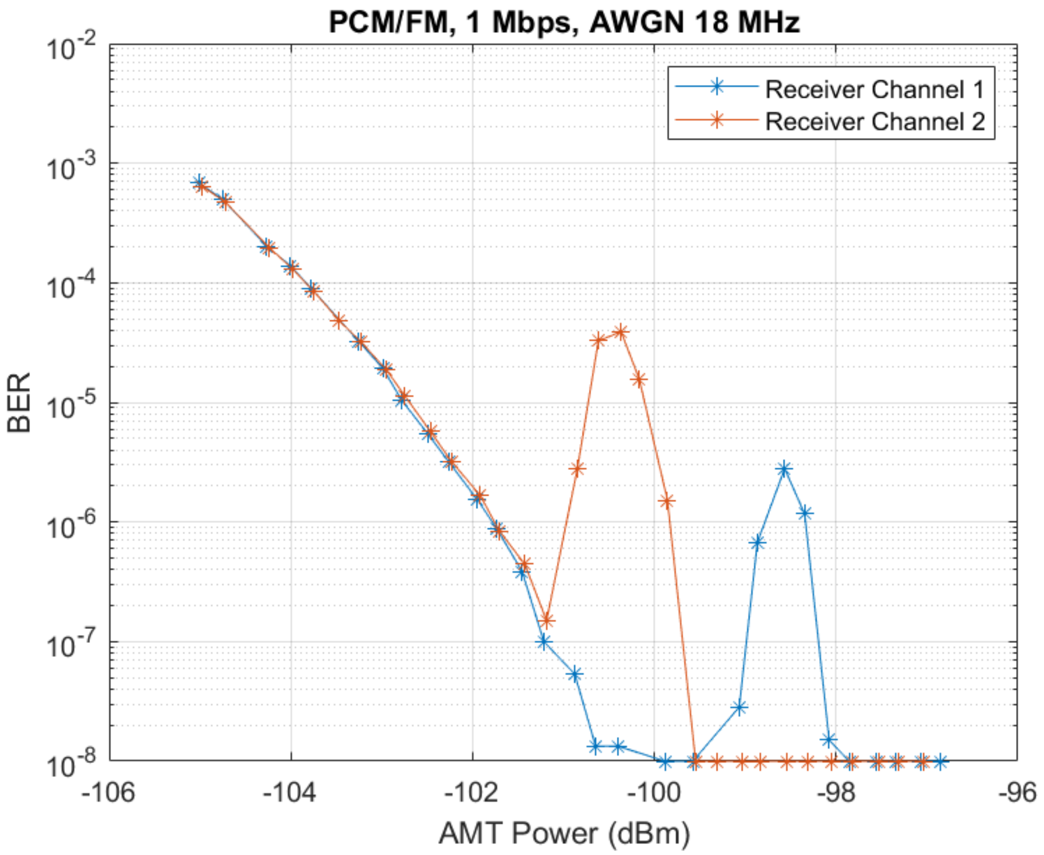
Spurious out-of-band emissions in Az 198 waveform land in AMT band



No correlation between OOBE in AMT band and LTE transmissions.
OOBE could be due to non-LTE emitter.

Anomalous Result – Main Experiment: PCM/FM 1 Mbps





Results from Bedford testbed; similar unanticipated receiver behavior observed on both testbeds

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Summary of Experiments

- **Pilot Study**
  - Goals: Verifying testbed automation & obtain preliminary data
- **Frequency Offset Experiment**
  - Objective: Characterize effect of shifting AMT center frequency relative to ABE
- **Main Experiment**
  - Objective: Assess impact of different ABE types on AMT receiver performance
- **Side Experiment A: Equalizer**
  - Objective: Assess impact of enabling equalizer in the presence of ABE
- **Side Experiment B: Space-Time Coding**
  - Objective: Assess impact of STC option in the presence of ABE
- **Side Experiment C: Excess Noise**
  - Objective: Assess impact of in-band excess white noise on AMT performance

➢ **4,723 unique test configurations, 12,571 valid tests**

Conclusions

- The frequency offset experiment results suggest that the IRIG back-off calculations work for most of the test ABE types.
- Careful consideration of OOBE characteristics is important
  - Simulation or emulation of ABE does not generally reflect real-world features
  - Two ABE waveforms with nearly equivalent average powers but with seemingly inconsequential differences in OOBE behavior can cause very different impacts on the AMT system. This is clear in the frequency offset results.
- The concept of equivalent in-band ambient noise (E_b/N_o loss) is demonstrated and supports interpretation of impacts on receiver performance.

Publication Information

- NASCTN Program
  - https://www.nist.gov/ctl/nasctn
- Project Page
  - https://www.nist.gov/programs-projects/aws-3-lte-impacts-amt
- Reports
  - *AWS-3 LTE Impacts on Aeronautical Mobile Telemetry*
    - Report: https://doi.org/10.6028/NIST.TN.2140
    - Data: https://data.nist.gov/od/id/mds2-2279
  - *In-Situ Captures of AWS-1 LTE for Aeronautical Mobile Telemetry System Evaluation*
    - Report: https://www.its.bldrdoc.gov/publications/details.aspx?pub=3262
  - *Laboratory Method for Recording AWS-3 LTE Waveforms*
    - Report: https://doi.org/10.6028/NIST.TN.2159
    - Data: https://doi.org/10.18434/mds2-2395

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Back Up Slides

Test Plan Review

Measurements and improved methodology to determine the impact of LTE on AMT systems.

Project comprises three major integrated tasks:

1. Test effects on AMT using a curated set of LTE waveforms of varying signaling conditions
2. Develop a Library LTE waveforms for this and future testing (captured from laboratory and in situ settings)
3. In situ captures using AMT infrastructure to inform scenario development for current and future testing (using deployed AWS-1 as a stand in for AWS-3)

Backup Slide – IF Filter Selection by the Receiver

	PCM/FM	SOQPSK	ARTM CPM	SOQPSK – FEC	STC	STC - FEC
1 Mbps	2 MHz	1.4 MHz	Not Tested	2 MHz	Not Tested	Not Tested
5 Mpbs	10 MHz	6 MHz	6 MHz	10 MHz	6 MHz	10 MHz
10 Mbps	20 MHz	14 MHz	10 MHz	20 MHz	14 MHz	20 MHz
20 Mbps	Not Tested	28 MHz	20 MHz	40 MHz	28 MHz	40 MHz

Side Experiment

Modulation Type	Data Rate (Mbps)			
PCM/FM	1	5	10	
SOQPSK	1	5	10	20
SOQPSK- FEC	1	5	10	20
ARTM CPM		5	10	20

Priority shown in yellow

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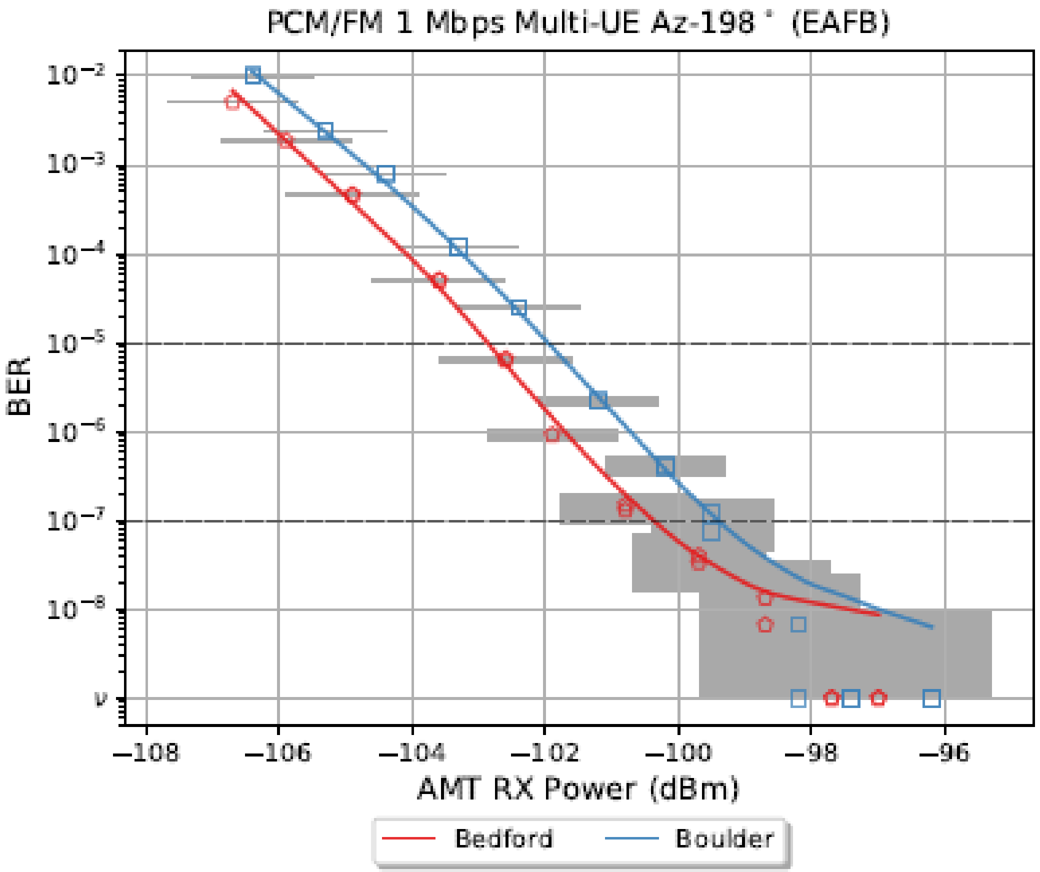
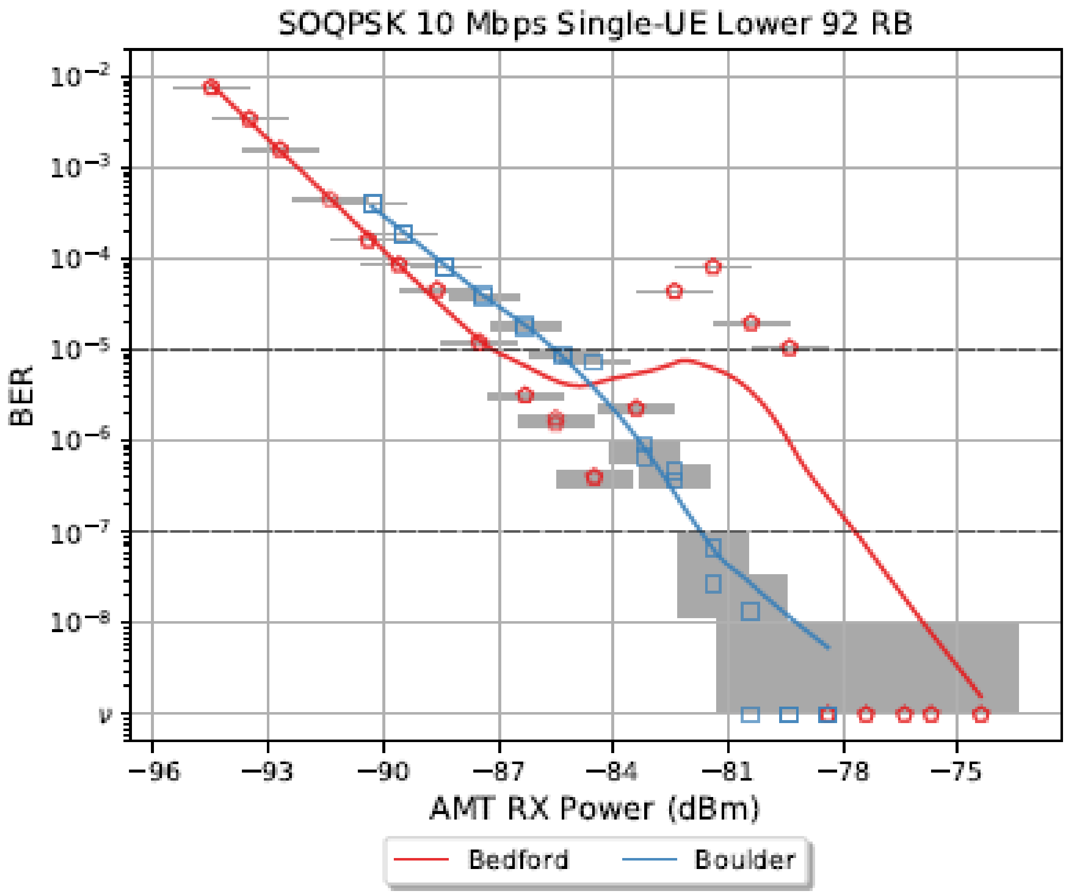
Testbed Comparison

Example of Consistent Result



Example of Inconsistent Result



Waveforms

4G-LTE Scheduling of UL resources

- LTE Systems interleave/“schedule” uplink broadcasts within the overall allocation
- Scheduling dynamics are derived from several settings within a base station – often customized by cellular operators

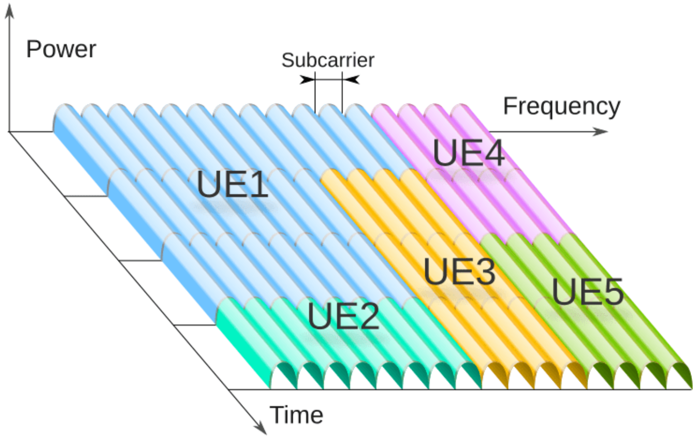
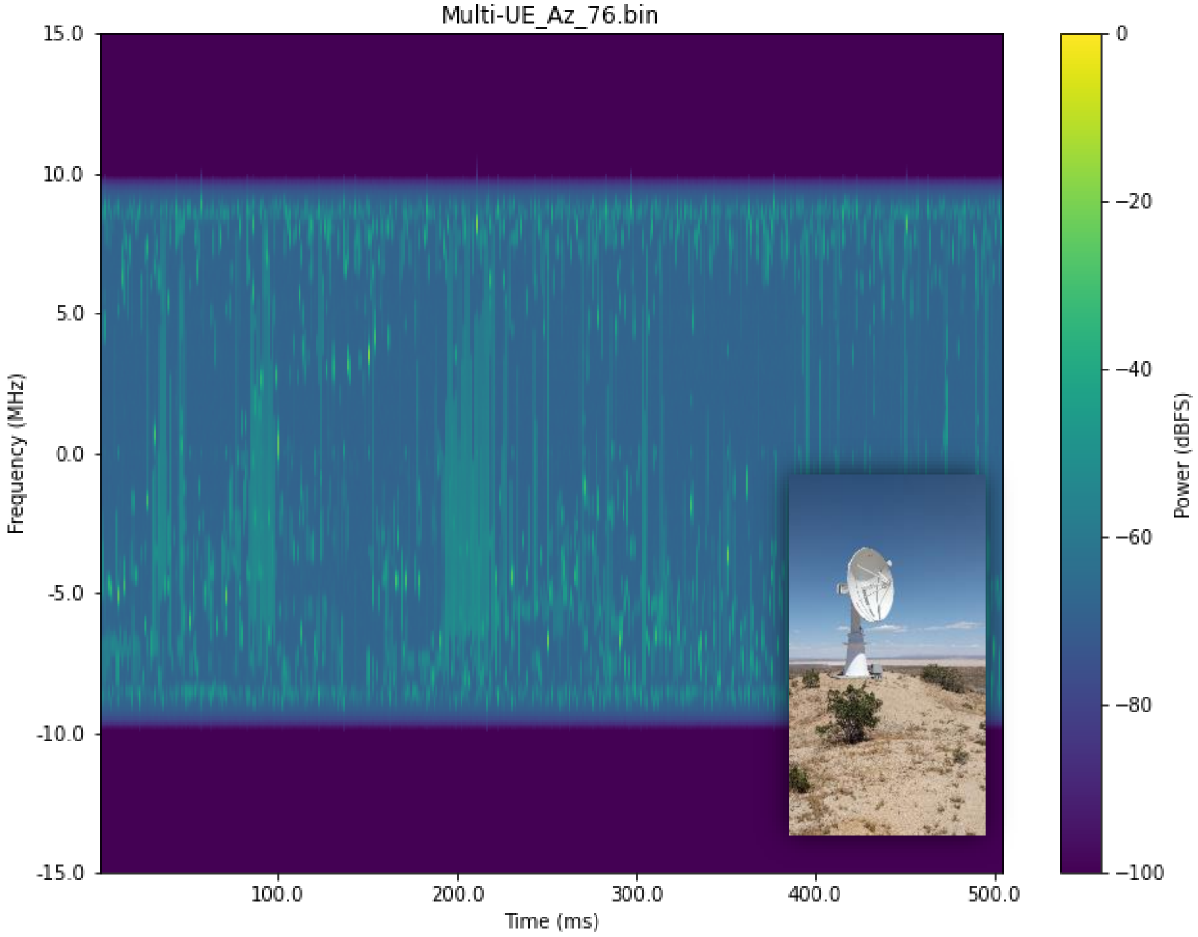


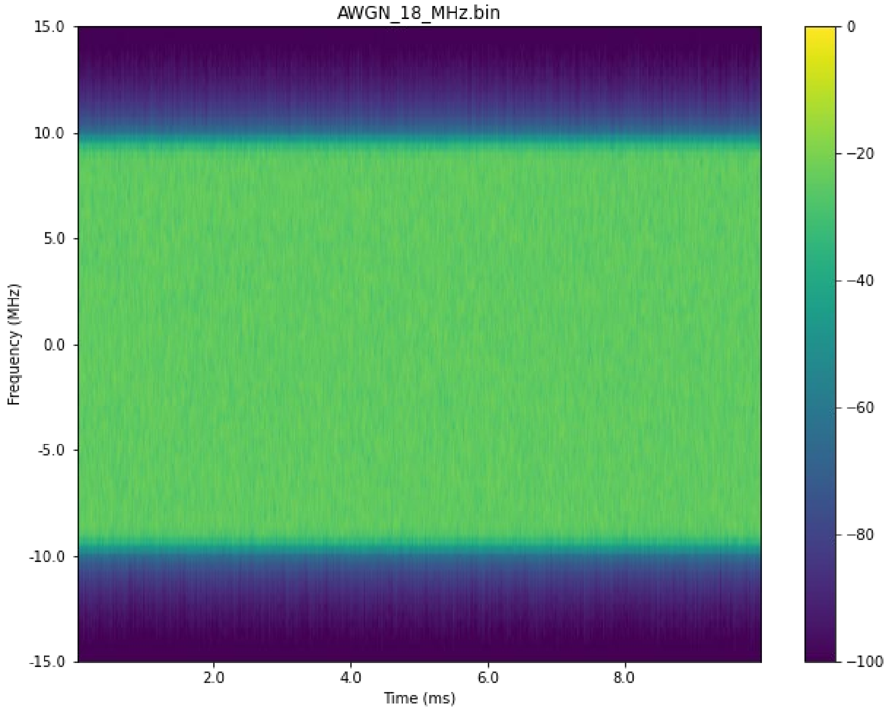
Image credit: https://yatebts.com/an-introduction-to-the-lte-mac-scheduler/

- Capture of UE emissions in a 20 MHz uplink allocation obtained through a *high gain* aeronautical mobile telemetry – tracking antenna

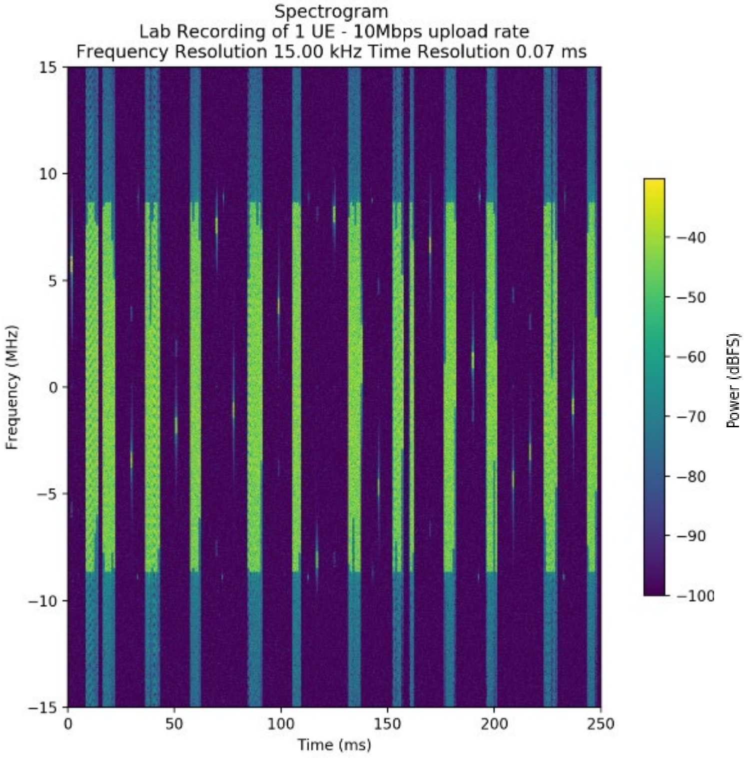


Comparison of Waveforms

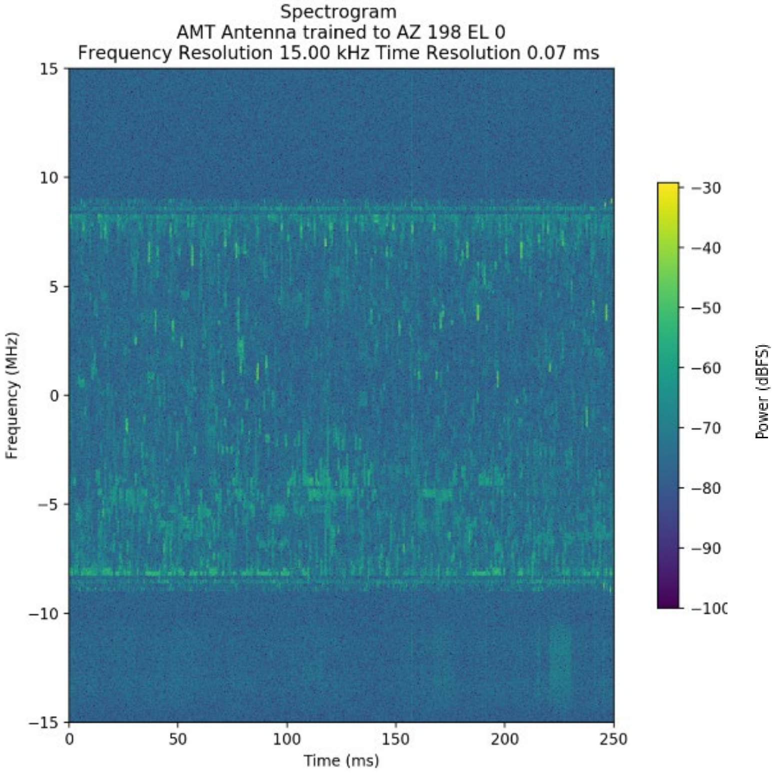
AWGN as generated in a VSG



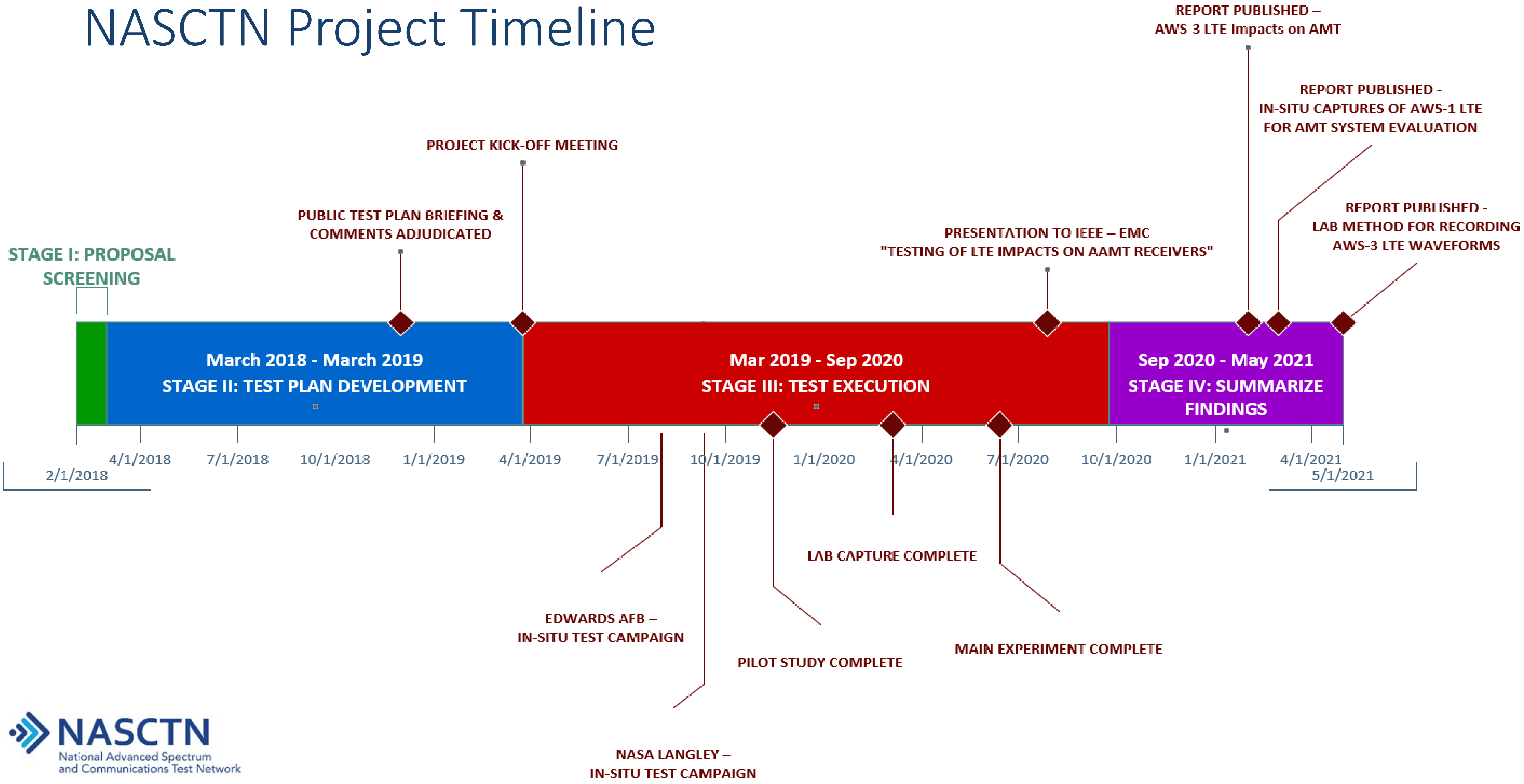
Single UE as captured in a laboratory environment



Multiple-UE as captured in the field with high directivity Antenna



NASCTN Project Timeline



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