NASCTN Plan [P-18-1]

Advanced Wireless Service 3 (AWS-3) Long-Term Evolution (LTE) Impacts on Aeronautical Mobile Telemetry (AMT) Test and Metrology Test Plan

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December 15, 2018

NASCTN

National Advanced Spectrum and Communications Test Network

National Advanced Spectrum and Communications Test Network (NASCTN)

The mission of the National Advanced Spectrum and Communications Test Network (NASCTN) is 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.

NASCTN was formed to provide a single focal point for engaging industry, academia, and other government agencies on advanced spectrum technologies, including testing, measurement, validation, and conformity assessment. The National Institute of Standards and Technology (NIST) hosts the NASCTN capability at the Department of Commerce Boulder Laboratories in Boulder, Colorado.

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- Ensure all spectrum sharing efforts are identified to other interested members.

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- National Science Foundation (NSF)
- National Telecommunications and Information Administration (NTIA)
- National Aeronautics and Space Administration (NASA)

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Preface

The National Advanced Spectrum and Communications Test Network (NASCTN) provides an impartial, scientifically rigorous forum for addressing spectrum-sharing challenges in an effort to accelerate the deployment of wireless technologies among commercial and federal users and to measure the impacts of spectrum dependent systems deployments.

NASCTN's mission is to provide robust test processes, validated measurement data, and statistical analysis 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.

Representatives from Edwards Air Force Base (EAFB) submitted a proposal to NASCTN to measure long-term evolution (LTE) User Equipment (UE) emissions in the United States Advanced Wireless Service (AWS)-3 frequency band (1755-1780 MHz) and aeronautical mobile telemetry (AMT) systems in the adjacent L-Band (1780-1850 MHz). This proposal builds on and extends a previous NASCTN project that measured the out of band (OoB) LTE evolved Node B (eNB) and UE AWS-3 emissions into adjacent L and S (2200-2395 MHz) frequency band AMT systems. The results of the previous NASCTN project are documented in NIST Technical Note TN-1980 [1]. While the previous test measured general LTE OoB emissions, this project specifically measures the impact to AMT systems.

After the NASCTN steering committee accepted the EAFB proposal as a NASCTN test, a test plan development team was assembled composed of experienced engineers and other professionals. The results of that work plus the knowledge and creativity of the team members culminated in the production of this test plan.

The test plan is designed to yield reproducible measurements. This NASCTN effort focuses on impacts of LTE UE AWS-3 activities to AMT activities in the adjacent L-Band. NASCTN will solicit comments about the test plan from the engineering community within federal and non-federal groups and entities.

Contents

Disclaimer ii

Preface iii

List of Figures vi

List of Tables vii

Executive Summary viii

1. Introduction 1
   - 1.1. Background 2
   - 1.2. Objectives 4
   - 1.3. Scope 4
   - 1.4. Deliverables 5

2. Test Methods 6
   - 2.1. Power Measurements 6
   - 2.2. Key Performance Indicators (KPIs) 8
   - 2.3. Devices Under Test (DUTs) 9
     - 2.3.1. Test Signals 9
     - 2.3.2. LTE Waveforms 9
     - 2.3.3. AMT 11
   - 2.4. Measurement Equipment 11
   - 2.5. Measurement Setup 11
   - 2.6. Measurement Procedures 13
   - 2.7. Calibration and Verification Procedure 14
   - 2.8. Measurement Location(s) 16

3. Statistical Test Design 17
   - 3.1. Overview 17
   - 3.2. Problem Scope and Test Objectives 17
   - 3.3. Response Variables 18
   - 3.4. Control Variable Considerations: 18
   - 3.5. Plan for Testing 18
     - 3.5.1. Near LTE Condition 19
     - 3.5.2. Far LTE Condition 19
   - 3.6. Final Test Space Coverage (subject to change) 20
   - 3.7. Final AMT Testing Strategy 21
   - 3.8. Statistical Data Analysis and Evaluation Plan 21

4. Test Support 22
   - 4.1. Coordination and Outreach 22
   - 4.2. Data Management 22

4.3. Safety 22
4.4. Project Tasks 23
5. References 24
6. Acronyms 26
Appendix A – Design of Experiment 28
Appendix B – D-Optimal Split-Split-Plot Run Matrix 30
Appendix C – Test Plan Compared to Existing Test Methods 34

List of Figures

Figure 1. Description of AWS-3 band. 2
Figure 2. Frequency bands of interest for this test. 3
Figure 3. Operational View of Test 4
Figure 4. LTE OoB Emissions extending into the Federal band 6
Figure 5. Test scenario concept 7
Figure 6. Delta path loss for two 100 meter-spaced UE 8
Figure 7. Response versus KPIs 8
Figure 8. OoB of UEs from NIST TN-1980 10
Figure 9. Basic RF elements and connections of the test setup. 12
Figure 10. Instrument control and data collection connectivity for the test setup 13
Figure 11. Design of Experiment. 28
Figure 12. DOE-based Test Design Framework 29
Figure 13. LTE interference effects across one KPI versus multiple KPIs 35

List of Tables

Table 1. List of Test Equipment 11
Table 2. Example of uncertainty values collected during the calibration and verification process.. 15
Table 3. Test Space Coverage.. 20
Table 4. Attributes of DOE-based Test Design 29
Table 5. D-Optimal Split-Split-Plot Run Matrix (176-run, 16-flights) 30
Table 9. comparison of control factors and response variables (subject to change after pre-test activities) 34

Executive Summary

The purpose of this NASCTN project is to establish a test methodology and perform laboratory measurements of L-Band aeronautical mobile telemetry (AMT) system performance in the presence of adjacent-band Long Term Evolution (LTE) uplink emissions. The LTE user equipment (UE) operates in the United States Advanced Wireless Service 3[1] (AWS-3) frequency band and the AMT systems operate in the adjacent 1780 – 1850 MHz federal frequency band. This test plan provides a repeatable and disciplined test methodology for measuring and analyzing the impact to AMT systems from AWS-3 equipment emissions. The test execution will demonstrate the methodology and produce a report of the effects on AMT in the presence of varying levels of LTE signal power into the AMT receiver.

The test is divided into three primary objectives:

1 – Determine the impact of LTE on AMT systems using a combination of sensitivity and susceptibility analysis.
2 – Curate a catalog of LTE waveforms representing conditions encountered by AMT systems for use within the testing and to be used after the test by the AMT community.
3 – Conduct in-situ LTE measurements using AMT receivers to inform the first two objectives.

This plan is intended to ensure these fundamental goals:

- a transparent, well-calibrated test method
- a clear path from measurement setup to data collection and analyzed results
- statistics-based data analysis

To provide a controlled setting, the NASCTN team is focusing on a conducted (over cables) test environment for the first test objective. Testing over cables allows for control over many of the factors under test. The waveforms used in this testing assume some basic features of a communication system architecture. The plan includes baseline and simultaneous emissions of LTE UE / AMT in adjacent spectrum. In actual field deployments, LTE UE emission behavior varies in power, user density, and duty cycle therefore a subset of these behaviors will be used in the testing. Likewise, AMT has many settings and deployment scenarios, and a consensus-driven subset of these behaviors will be used in testing.

To support and complement the main impact analysis testing, NASCTN will generate and collect a catalog of LTE waveforms that represent likely and other identified conditions AMT receiver systems will experience. This catalog of waveforms will be informed by in-situ measurements of LTE emissions using real AMT receivers to determine what waveforms and conditions are most likely encountered at deployed AMT locations.

NASCTN will solicit and adjudicate comments on this test plan from the LTE and AMT stakeholders within the federal and non-federal communities.

[1] AWS-3 is known in LTE parlance as Band 66 which was licensed for low-power uplink in the 1755-1780 MHz band, paired with high power downlink in the 2155-2180 MHz band. Source: http://wireless.fcc.gov/auctions/default.htm?job=auction_summary&id=97

LTE Impacts on AMT
Test and Metrology Test Plan

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Abstract: A test plan for measuring the impact of long-term evolution (LTE) uplink emissions on aeronautical mobile telemetry (AMT) systems is presented that ensures objective, repeatable, and reproducible measurement results. The test plan describes emission measurements that will be performed by National Advanced Spectrum and Communications Test Network (NASCTN) on a variety of LTE emissions on a sample of AMT equipment. These measurements will provide data on emissions from advanced wireless service 3 (AWS-3) equipment and their impact on AMT systems. NASCTN will also curate a catalog of LTE waveforms that represent waveforms of interest to be encountered by AMT systems using a combination of laboratory and field collections. The data may inform interference analyses for band sharing studies, including frequency and distance separation parameters between LTE hardware and telemetry receiving systems. The data collected could inform conditions of harmful interference from UEs to telemetry links. The test methods are intended to affirm or provide potential improvements to existing AMT coexistence testing methods. It is not the goal of this test to make determinations on harmful interference or make spectrum regulation determinations.

Keywords: advanced wireless service 3 (AWS-3); band sharing; band sharing analysis; emission spectrum; interference analysis; long-term evolution (LTE); national advanced spectrum and communications test network (NASCTN); telemetry links; user equipment (UE); 1755-1780 MHz, 1780-1850 MHz; aeronautical mobile telemetry (AMT); spectrum measurements.

1. Introduction

Edwards Air Force Base (EAFB) proposed a measurement campaign to the National Advanced Spectrum and Communications Test Network (NASCTN) to measure and analyze L-Band (1780-1850 MHz) aeronautical mobile telemetry (AMT) system effects in the presence of varying levels of adjacent band long-term evolution (LTE) user equipment (UE). In the advanced

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wireless service 3 (AWS-3) band LTE uplink of user devices are slated to operate between1755 MHz and 1780 MHz).

This plan describes a series of controlled laboratory measurements of key parameters to the operation of an AMT system across a variety of LTE UE signaling conditions. This plan describes a methodology, test execution, and the data analysis needed to produce the final report.

To support the laboratory test, NASCTN will also develop a catalog of LTE waveforms to serve as the added signal. The catalog will use a combination of laboratory and field measurement collections to represent the types of LTE waveforms ATM systems could encounter at deployed locations.

1.1. Background

In the 2010 Presidential Memorandum on Unleashing the Wireless Broadband Revolution [2], the National Telecommunications and Information Administration (NTIA) was tasked to identify underutilized spectrum suitable for wireless broadband use. In the subsequent NTIA Fast Track Report [3], many federal bands were identified as commercially viable. From this report, the Federal Communication Commission (FCC) identified 1695 MHz to 1710 MHz, 1755 MHz to 1780 MHz, and 2155 MHz to 2180 MHz together as the 3rd advanced wireless services group of bands (called together AWS-3) in July 2013, shown in Figure 1. The FCC adopted a Report and Order in March 2014 with allocation, technical, and licensing rules for commercial use of the AWS-3 bands [4]. The uplink blocks of interest here are the 5 MHz blocks labeled G, H, and I and the 10 MHz J block.

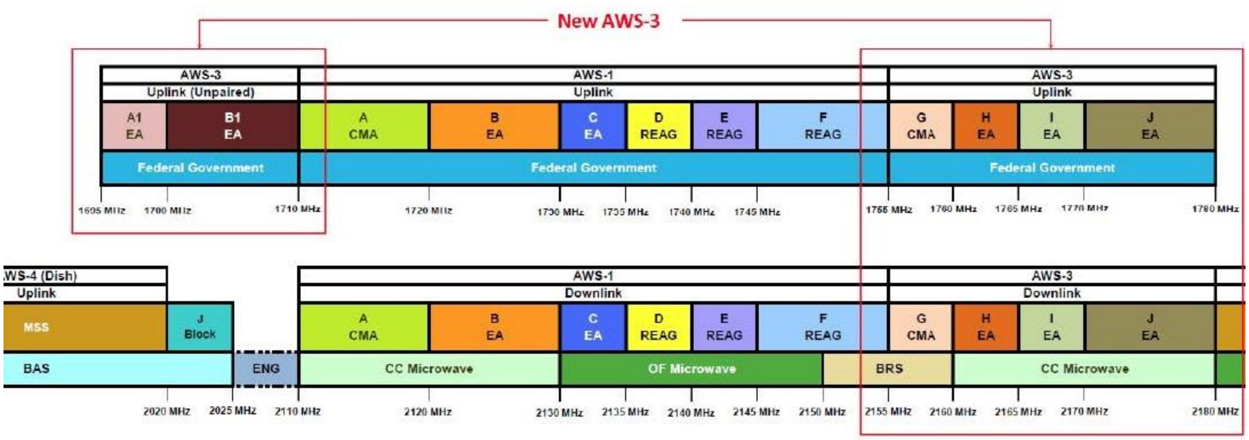

Figure 1. Description of AWS-3 band.

Through Auction 97 [5], the AWS-3 band was auctioned for commercial mobile broadband usage in the United States. The auction raised $41B in revenue for the United States Treasury and required federal agencies in the AWS-3 band to look for other ways to accomplish their missions. In the 1755 MHz to 1780 MHz portion of the AWS-3 band, the DoD is using a combination of sharing, compression, and relocation to other bands (including the 2025 MHz to 2110 MHz band).

The FCC is issuing licenses for the introduction of new mobile radio systems into the 1755–1780 MHz (uplink) and 2155–2180 MHz (downlink). Emissions from LTE devices have the potential to impact operation of adjacent-band AMT systems that operate in the 1780–1850 MHz (L-Band). This part of the frequency spectrum is depicted in Figure 2.

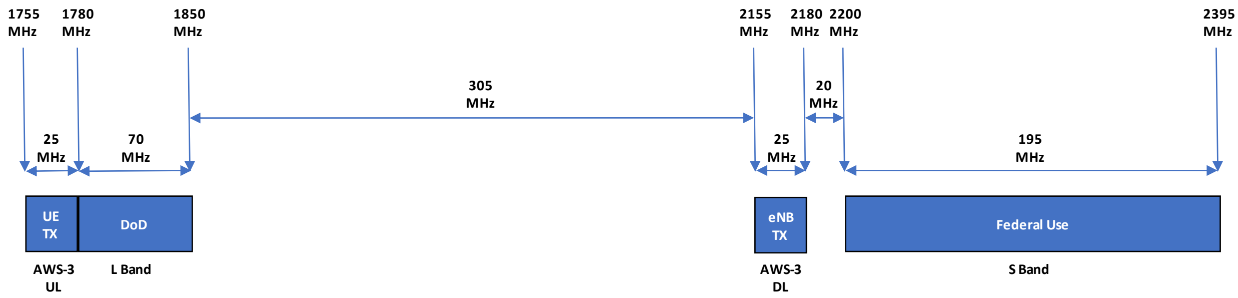

Figure 2. Frequency bands of interest for this test.

Regarding the new AWS-3 LTE UE systems that will deploy in the 1755–1780 MHz spectrum, the adjacent-band telemetry systems are air-to-ground links that support U.S. flight-test and space operations. These links use high-gain antennas that may be pointed at elevation angles approaching 0 degrees (the horizon). This condition is due to systems mission requirement to support long link ranges between airborne test platforms and ground stations to track airborne platforms carrying telemetry transmitters. The airborne telemetry transmitter signals are received ground-based telemetry antennas which then feed into ground-based telemetry receivers for reception of real-time data feeds that can be monitored, recorded and analyzed.

Detailed measurements and analyses need to be performed to determine the potential impact of AWS-3 LTE UE emissions on AMT systems. These measurements are valuable in that they could inform on spectrum sharing and collision avoidance and how much off-tuning (number of megahertz) or distance separation (number of kilometers) are needed between transmitters and telemetry receiver stations to avoid harmful interference[6] to the telemetry receivers.

LTE transmission, reception, OoB limits, and testing are governed by 3rd Generation Partnership Project (3GPP) specifications [6][7][8].

AMT standards are developed and maintained by the Range Commander's Council (RCC) Telemetry Group [9]. IRIG 106 Appendix 2F states protection criteria for AMT systems in all the available telemetry bands. Protection criteria for telemetry systems in the aeronautical mobile service are defined and maintained by the International Telecommunications Union (ITU) [10].

[6] It is not in the mission of NASCTN to provide recommendations about spectrum sharing, or what impacts describe harmful interference.

Test ideas are influenced and informed by previous NASCTN projects [11] and independent studies by others, such as [12].

Figure 3 provides a high-level operational view of how LTE UE emissions could enter the AMT link. In Figure 3, the blue shape is intended signals and the red is unintended signals. The NASCTN test will seek to duplicate this scenario in a controlled laboratory environment. Details on the equipment, setup, and procedures are provided in Section 2.

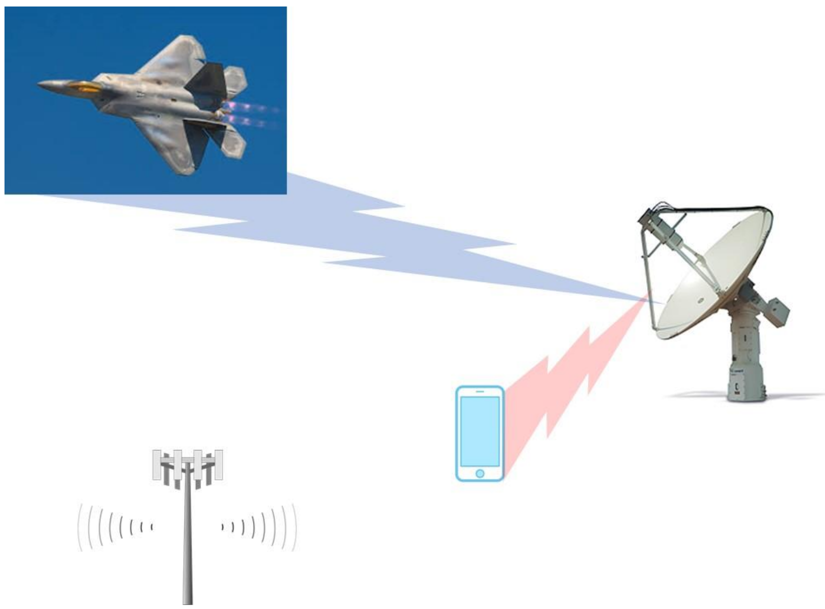

Figure 3. Operational View of Test

1.2. Objectives

The overall objective of this test plan is to develop a methodology that quantifies the effects on AMT systems in the presence of uplink LTE adjacent-band emissions. This analysis will be accomplished through three separate but related objectives:

1 – Determine the impact of LTE on AMT systems using a combination of sensitivity and susceptibility analyses, presented as absolute powers and carrier to interference ratios.
2 – Curate a catalog of LTE waveforms representing conditions encountered by AMT systems for use within the testing and to be used after the test by the AMT community.
3 – Conduct in-situ LTE measurements using AMT antenna platforms or equivalent to inform the first two objectives.

1.3. Scope

The test method discussed here focuses on a conducted (over cables) setup with settings intended to reproduce the setup shown in Figure 3. This test measures the LTE impacts on AMT, not AMT impacts to LTE. While collecting data and analyzing the impact to LTE may also be of interest, there is no sponsor requesting such testing, and it is beyond the scope of this test.

A key aspect in the investigation is to understand the quality and availability of response variables for AMT systems. These response variables are a subset of AMT's key performance indicators (KPIs) and provide an indication of the impact of LTE emissions to the AMT systems. A specific response variable recorded from software or a piece of test equipment will be referred to as a measurand. When possible, each measurand will be given with bounds of certainty. Emphasis is on real-world expected signals. However, where practical, the signal levels will cover a range of power levels that could inform system architecture considerations.

An important consideration in the testing is the specifics of the LTE waveform. The UE uplink closest (uppermost block is the J-block, 1770-1780 MHz) to the AMT band is considered the block most likely to cause disruption.

1.4. Deliverables

- A test plan which includes a repeatable test methodology to collect LTE UE and AMT data
- A set of raw and processed data from lab testing to validate test methodology
- List of key response variables (with confidence bounds) that indicate an impact on AMT systems (such as AMT KPIs versus interference power)
- Analysis techniques and results to capture impact of LTE on AMT systems
- Catalog of LTE waveforms (frequency agnostic frequency domain duplexed (FDD) In-Phase and Quadrature (IQ) waveforms categorized by LTE parameters)
- AMT KPI response curves as parameterized by LTE waveforms that are included in the catalog

2. Test Methods

As a high-level explanation, varying levels of adjacent band LTE UE power (Section 2.1) and varying LTE characteristics and quantities (Section 2.3) will be applied to a telemetry link in a laboratory setting to determine effects on system KPIs (Section 2.2) as a function of AMT and LTE signal levels.

2.1. Power Measurements

Figure 4 shows a qualitative drawing of LTE uplink (UE) energy as it extends in to the 1780 – 1850 MHz band. Labels A, B, and C of Figure 4 represent LTE energy that is in-band to AMT and out of band to LTE UEs. According to the proposers of this test from EAFB, some AMT receivers use Radio Frequency (RF) pre-selector filters attempt to filter out the 1710-1755 MHz LTE-in-band energy (from the LTE AWS-1 band). Other AMT receivers have no filtration and LTE energy (in-band and OoB) from AWS-1 and AWS-3 bands is allowed in to the receiver. Therefore, all of the LTE energy is a concern to an AMT receiver.

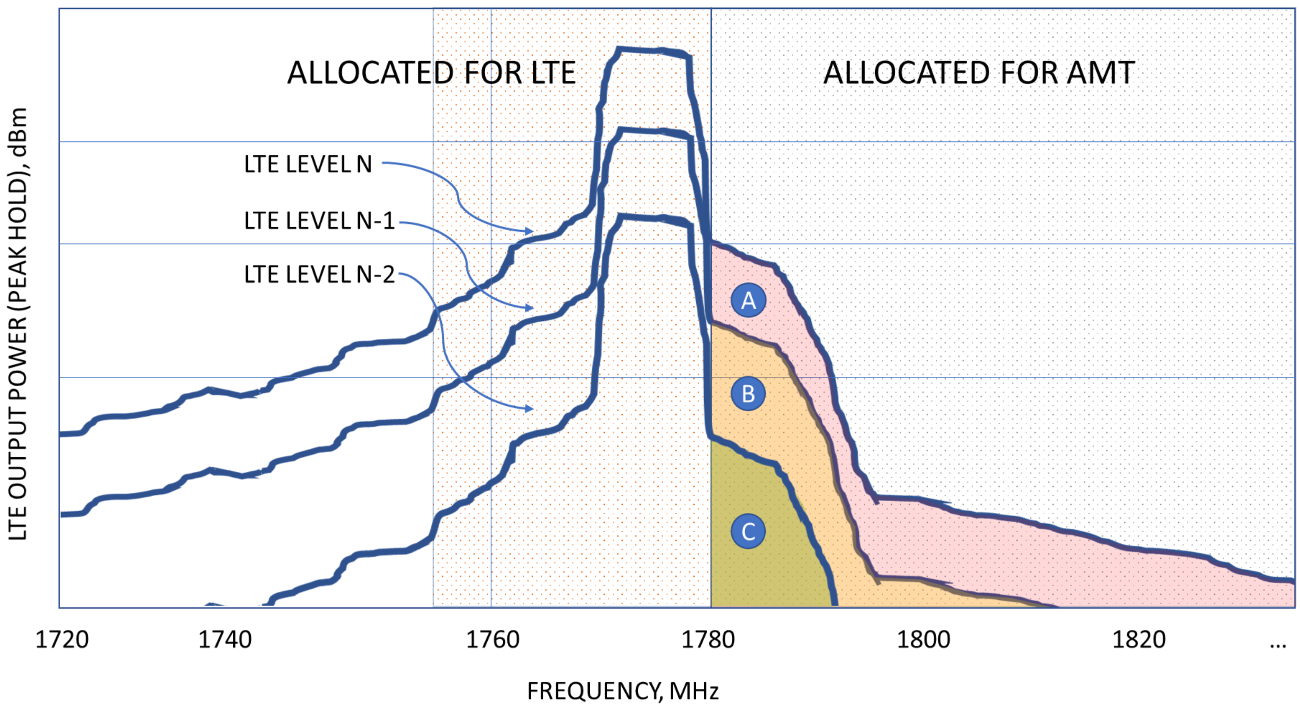

Figure 4. LTE OoB Emissions extending into the Federal band

Where possible, actual deployable telemetry transmitters and receivers will be used for the test in a laboratory setting. The proposed test method allows a high degree of control over the RF conditions at the AMT receiver (AMT Rx). The test setup proposes the playback of captured, LTE uplink waveforms from a full stack implemented COTS system (including aggregate behavior from an LTE cell (or to be determined cells)). If the LTE waveform is generated in real-time from a UE, a separate path between the eNB and the UE will be necessary to establish connectivity between the two elements of the LTE system. In general, due to the complexity of

LTE signaling, a surrogate LTE waveform created from the capture of actual LTE behavior may be desirable for repeatability and uncertainty analysis. The selection of LTE waveforms will be influenced by laboratory generated waveforms along with in-situ measurements of LTE emissions using AMT antenna and signal conditioning architectures or equivalent.

Commercial and federal test ranges that support AMT missions have fixed and transportable receive assets with high-gain parabolic dishes, with typical dimensions of 4', 6', 8', 10', 15', and 30' in diameter. An estimate of the antenna gains is found using the following equation.

$$G = 10\log_{10}\left[\eta\left(\frac{\pi D}{\lambda}\right)^2\right],$$

where G= antenna gain over an isotropic source, η = antenna efficiency, D = diameter of the parabolic reflector in meters, and λ = wavelength of the signal in meters. Thus, for antenna efficiencies between 35% to 55%, with frequencies between 1750 MHz to 1850 MHz, the gain will range from approximately 9 dB to 20 dB. These gain figures need to be budgeted for in the test bed.

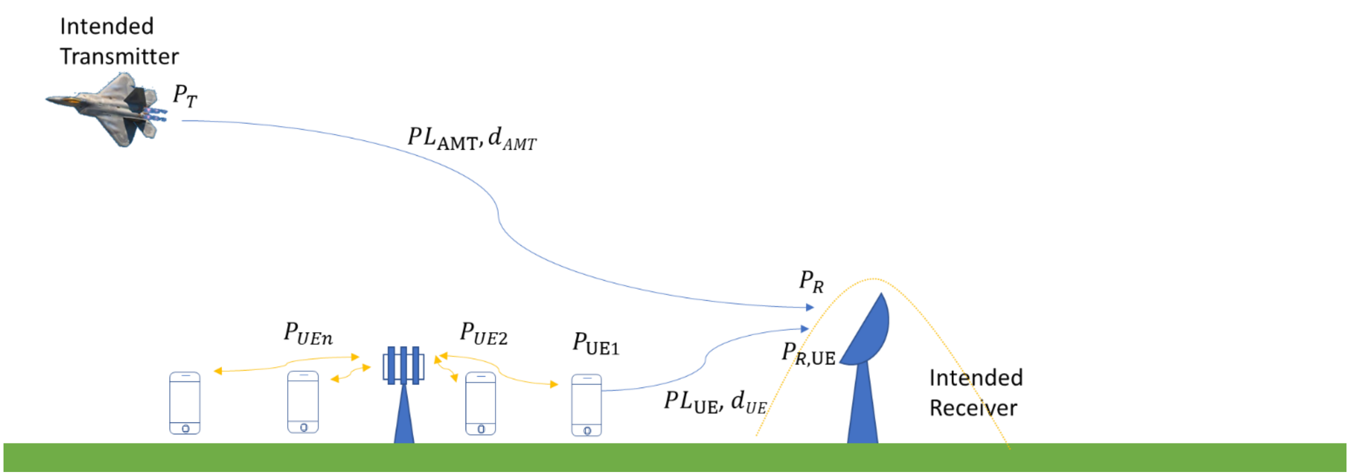

Figure 5. Test scenario concept

Figure 5 depicts the test scenario in more detail. All factors are treated as random variables and are defined as:

P_T = telemetry transmitter equivalent isotropic radiated power (EIRP), in dBm

PL_{AMT}, PL_{UE}, PL_N = path loss values, in dB

d_{AMT}, d_{UE} = distances, in km

P_R, $P_{R,UE}$ = telemetry ground station equivalent isotropic incident power (EIIP), in dBm

As mentioned in Section 2.3.2 in more detail; LTE UE powers do not add coherently. The LTE scheduling algorithm that dictates the uplink signal structures from a UE to the eNB governs the resource grants given to the UE. This impacts the resource block allocation, in time and frequency given to individual UEs in a given cell. In addition, the LTE assessed UE signal path to the eNB also impacts transmit power of the UE. In the simplest case, a UE near the eNB cell edge may radiate at higher power levels per resource block as compared to a UE in close proximity to an eNB. UEs far away from each other are emitting energy differing by many orders of magnitude. As distance increases, the change in power between neighboring UEs decreases accordingly. Therefore, this test campaign will attempt to develop waveforms to include multiple transmitting UEs with different UE to eNB signal condition profiles.

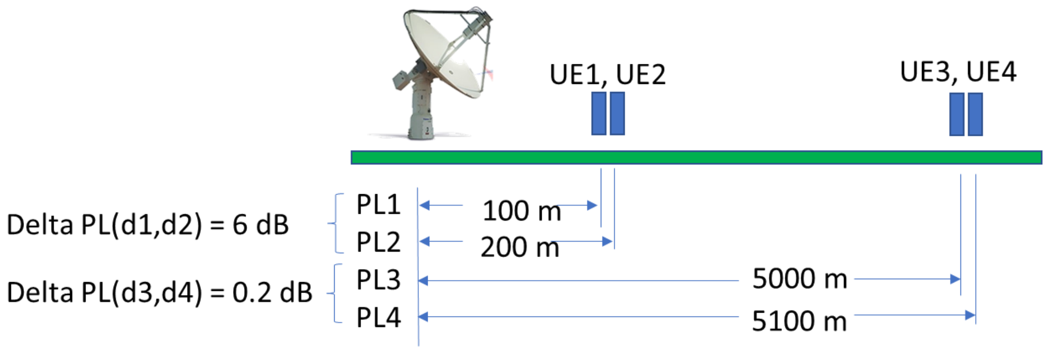

Figure 6. Delta path loss for two 100 meter-spaced UE

As an example of how power differs at a receiver, Figure 6 shows the delta path loss between two pairs of UEs that are spaced 100 meters apart. Using Friis equation: $PL(dB) = (P_{tx} + G_{tx})_{EIRP} + G_{rx} + 20log_{10}\left(\frac{\lambda}{4\pi d_N}\right)$, and using d1, d2, d3, and d4 for d_N. From this equation, UE2 is 6 dB lower in power at the telemetry receiver than UE1, and UE4 is 0.2 dB lower in power than UE3 at the telemetry receiver. Since a telemetry receiver uses a high gain dish, distant UEs can offer significant powers at a distance.

2.2. Key Performance Indicators (KPIs)

AMT systems include several response variables, the *most important* of which will be labeled as KPIs.

These KPIs define if the AMT systems are meeting their designed operation objectives. For this test, a subset of all AMT KPIs is evaluated as response variables to indicate if LTE emissions are impacting AMT operations. An initial list of KPIs evaluated as response variables for this test are:

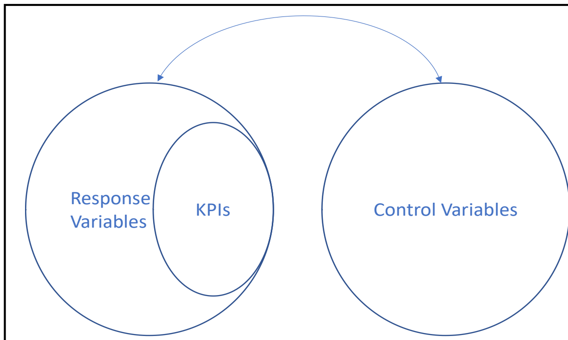

Figure 7. Response versus KPIs

- Bit synchronization
- BER distributions (from AMT receiver)
- Received signal strength indicator (RSSI)

Other AMT operating conditions also are included in the test considerations (control variables), an example of test considerations for this test is:

- Test AMT at a variety of AMT (signal strengths and modulation types), and variety of LTE conditions to arrive at various combinations of C/I. Additive testing with additional sources of noise to arrive at CINR.

2.3. Devices Under Test (DUTs)

2.3.1. Test Signals

An AMT link can be more susceptible to different types of interferers. The first testing phase is exploratory to determine which *type* of interference AMT is sensitive. The first phase of testing involves injecting synthesized test signals from a vector signal generator to investigate an AMT link's sensitivity to different types of interference. A test matrix for this portion will evolve through testing and will be included in the final report. Signals used for this activity will include (i) broadband white gaussian noise, (ii) narrow band white gaussian noise (180 kHz to mimic an LTE resource block), and a (iii) hopping resource block bandwidths. Each of these signal types will be applied to the AMT link at varying power levels. These waveforms will be first centered at the LTE uplink frequency allocation, however may be swept across the frequency band of interest to glean additional insights into AMT receiver susceptibility. The broadband noise represents an LTE network received from far away; the hopping 180 kHz mimics LTE UE equipment that is near an AMT receiver. For example, if the output of this exploratory phase demonstrates that AMT is much more sensitive to one type of interferer, it will focus the study on LTE waveforms that resemble those type of interferers. The goal of this phase is to narrow down the types of LTE signals and their characteristics investigated in the next steps.

2.3.2. LTE Waveforms

LTE energy enters an AMT receiving system (also known as ground station) in the AMT band (as an LTE OoB emission) and out of the AMT band (as an in-band LTE emission). LTE emissions are dynamic in power, frequency, and time dimensions. The fundamental unit of measure describing LTE emissions is the resource block. This resources block is 1 millisecond in time and 180 kilohertz (kHz) wide in frequency. The resource block is made up of twelve 15 kHz orthogonal frequency division multiplexing (OFDM) resource elements. The J-block of band 66 is 10 MHz wide, spanning from 1770 – 1780 MHz, and contains fifty resource blocks and two 500 kHz guard bands on each side. An LTE network (controlled by the eNB) is constantly distributing resource blocks to the UEs that have data to send. A UE may be attached to an eNB and have no data to transmit for the majority of a day. To better understand LTE emissions in the context of interference to receivers, there are many test efforts across federal and non-federal stakeholders quantifying the emissive behavior of UEs in the aggregate[7].

[7] Such as three projects sponsored by the National Spectrum Consortium(NSC), NSC-16-0401, NSC-16-0402, NSC-16-0403. Listed on the NSC website: https://www.nationalspectrumconsortium.org/project-awards/

UEs operating in an LTE network may fill the entire 10 MHz band or only a small portion (i.e., use a limited number of resource blocks). LTE emission characteristics need to be treated as a statistical distribution as those emissions are defined by LTE scheduling algorithms that dictate the frequency and temporal components. If enough UEs are summed together, the behavior is typically considered to approach white gaussian noise (WGN). From the perspective of a ground-based receiver, those aggregate conditions may not be met, for example, if a single UE is in close physical proximity to the AMT receiver. In this scenario, LTE uplink emissions could be dominated by the closest UE and the background UEs are many orders of magnitude lower in power. This phenomenon can be observed in LTE spectrum monitoring efforts such as an NTIA Institute for Telecommunication Sciences (ITS) interim report [13].

In a previous test NASCTN performed sponsored by Edwards AFB, the OOB emissions of handsets and eNBs were collected [1]. The shape and expected roll-off of UEs was captured with a dynamic range of more than 100 dB, shown in Figure 8.

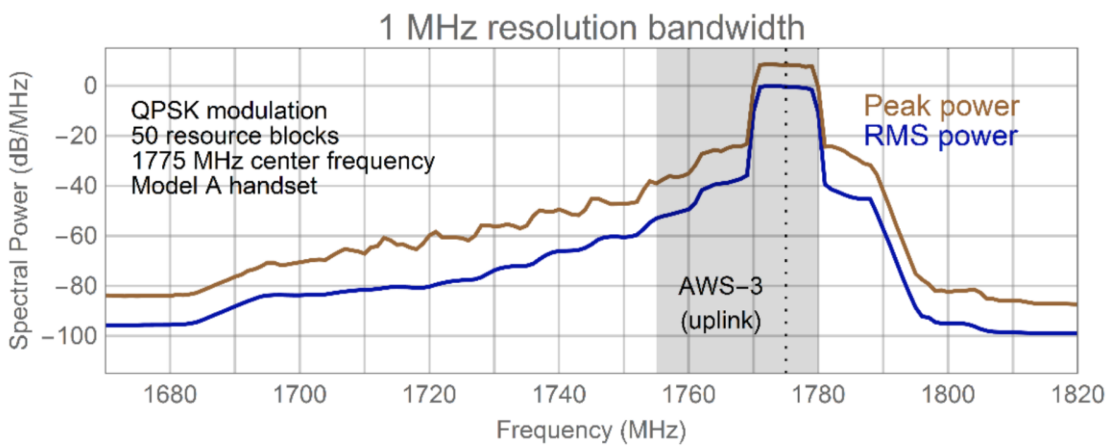

Figure 8. OoB of UEs from NIST TN-1980

This test was informative to the question of how much energy would be in the 1780 – 1850 MHz federal band but does not reveal the temporal or spurious components that may be a dominant interference mechanism to an AMT receiving system. Therefore, for this test, a time series of a UE, and multiple UEs will be used as an injected signal, or “interfering signal”.

The LTE UE emissions used for this test will include tests injecting a variety of LTE UE emissions that emulate operational LTE scenarios. Emphasis on which UE scenarios will be informed by the pretest activities and measurements of UEs from lab and field. An LTE cell commanded by the eNodeB coordinates user traffic by sharing resource blocks resulting in only a few UEs emitting at the same time per cell. The number of simultaneous UEs emitting in a cell is currently being measured by the ongoing NASCTN test titled *Aggregate LTE: Characterizing User Equipment Emissions* [14]. Comparing the emissions of actual UEs in laboratory and in-situ field measurements will inform the NASCTN test execution team which signals to use for the LTE portion of the test bed.

2.3.3. AMT

This test plan is focused on AMT equipment that operates in the upper L-Band, specifically 1780 – 1850 MHz. DoD telemetry operations are in the process of transitioning out of the AWS-3 band and upgrading hardware to coexist with LTE uplink emissions in the adjacent 1755 – 1780 MHz. AMT equipment has many variations in deployment locations (including transportable) and hardware. The test execution phase will be performed with AMT equipment agreed upon by the greater telemetry community as representative hardware. When possible, actual telemetry equipment will be used and KPIs extracted from its log files. The design of experiment is written to allow for two variations of telemetry hardware. Some factors the telemetry will be tested over include configurations such as modulation types (SOQPSK, SOQPSK-LDPC, and ARTM CPM).

2.4. Measurement Equipment

The list of equipment needed for the test shown in Table 1. Categories of the equipment includes items used to 1) create the RF test environment and waveforms, 2) collect data, 3) calibrate and verify the test setup, and 4) devices under test.

Table 1. List of Test Equipment

Equipment	Use
LTE Network	Commercial eNB for UE emission collection.
LTE Protocol Analyzer	Monitoring and collecting LTE network statistics
CMW500 Traffic Generator	LTE waveform generation
AMT Transmitter/Receivers	Serves as device under test (DUT) – example equipment is the receiver and receiver analyzer from Quasonix Equipment will be able to report AMT KPI that can be logged for further statistical analysis
Vector Signal Generator (VSG)	Generation of synthesized test waveforms and playback of LTE captures
Vector Network Analyzer (VNA)	Calibration and verification
Bit Error Rate (BER) Counter	Tracking BER of the AMT link
Spectrum Analyzer	Monitoring spectrum activity in the test bed
Power Meter	Calibration and verification
Vector Signal Analyzer (VSA)	Monitoring signal levels, and error vector magnitude
RF Combiner	Test bed
RF Programmable Attenuators	Test bed
RF Cables	Test bed
Data Storage	Test bed, telemetry data logging devices
Universal Serial Bus (USB)/Ethernet Hubs	Test bed

2.5. Measurement Setup

The proposed test method uses conducted connections between all elements of the test setup. Figure 9 is a high-level description of the connection paths between the LTE waveform generation and the AMT signal chain (e.g., the AMT Transmitter (Tx) to AMT Rx). In this setup, it is assumed that any handshaking between the AMT Tx and AMT Rx are handled by a separate path not subject to the impacts of the LTE waveform. Handshaking is not used in serial streaming telemetry. Figure 9 assumes the playback of a captured, surrogate LTE waveform. If the LTE waveform is generated in real-time from a UE, a separate path between the eNB and the UE will be necessary to establish connectivity between the two elements of the LTE system. The setup assumes that the LTE UE signal is not impacted by the AMT Tx to an extent that changes the UE waveform during transmission.

Figure 9 includes the ability to add white Gaussian noise into the signal chain if needed to raise the noise power over the inherent noise floor of the signal chain. This will allow a measure of signal-to-noise ratio (SNR) independent of the receiver. In this setup, the noise level is kept fixed once the level is set. Varying the AMT Tx and LTE waveforms will allow stepping through the desired carrier-to-noise-plus-interference (CNIR) ranges. The goal is to subject every receiver under test to the same CNR and CNIR conditions.

The AMT Rx should be placed into a shielded enclosure to avoid connection to the AMT Tx via a leakage path. This will also reduce the potential of other spurious RF signals from impacting the AMT Rx during the test.

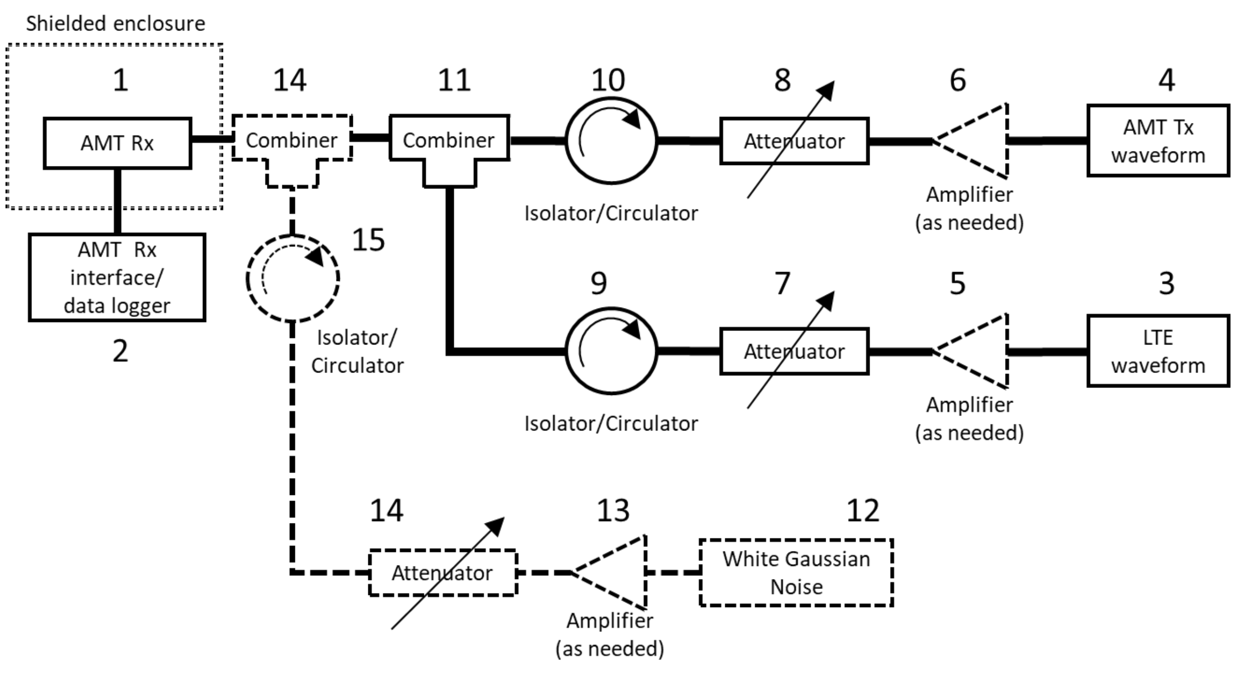

Figure 9. Basic RF elements and connections of the test setup.

A control architecture necessary for automation, synchronization, and data collection overlays the RF layout. Figure 10 illustrates connectivity to the various RF elements, including the programmable RF attenuators and the waveform generators. The connections may be a combination of interfaces, such as Ethernet, USB, and RS232. In this diagram, the computer/controller is shown as directly interfacing to the AMT Rx (the AMT Rx interface is grayed out). If additional hardware is used to interface with the AMT Rx, the computer/controller will connect to that hardware.

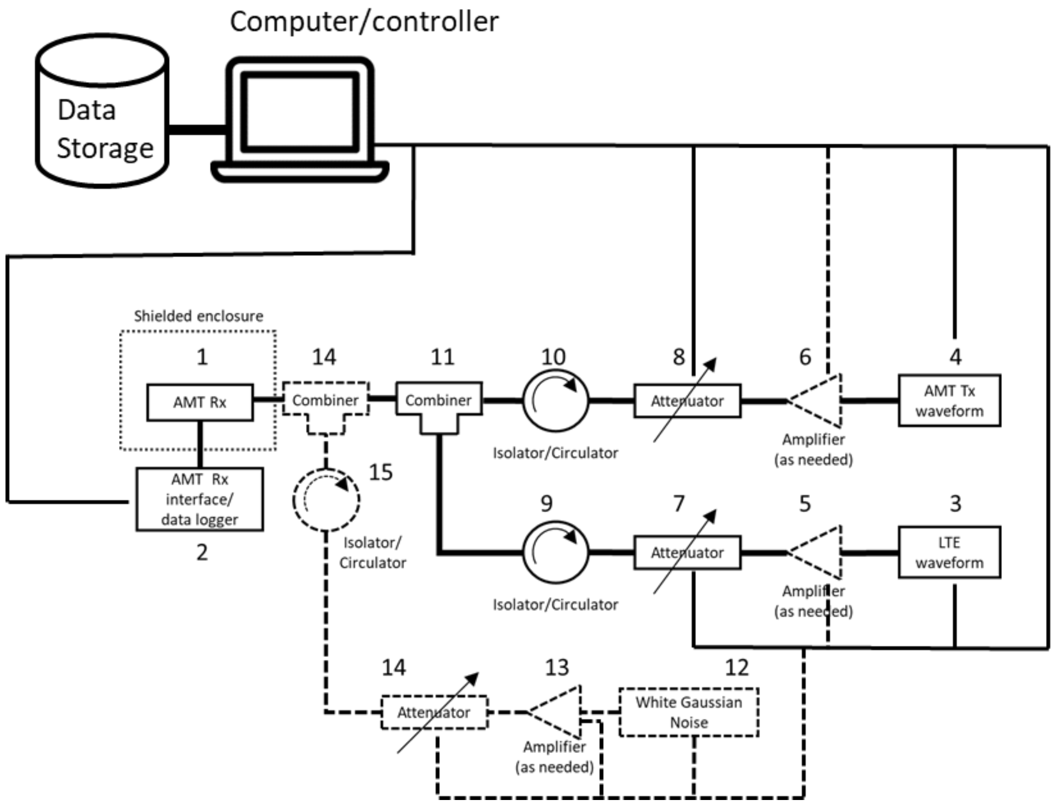

Figure 10. Instrument control and data collection connectivity for the test setup

Data parsing, processing and analysis is performed in an ex post fashion.

2.6. Measurement Procedures

The basic measurement procedure is to establish a connection between the AMT Tx (or surrogate) and the AMT Rx via the RF connection path shown in Figure 9. The AMT connection is initially established without LTE activity present to collect baseline KPI data. The amount of data collected (and time duration) will depend on statistical test design criteria discussed in Section 3.

With the AMT link established, an LTE surrogate waveform will be injected into the AMT RF channel via the RF combiner shown in Figure 9. The RF attenuation of the LTE waveform in the test setup will be fixed for a given test point so that any variations in the LTE waveform are due to the utilization of resource blocks and data encoding inherent to actual LTE system behavior.

The testing will cover a combination of AMT link signal strength) and LTE activity levels. A test matrix will be developed that captures the distinguishing elements of the AMT communications (e.g. path loss, modulation coding) and the LTE waveforms (e.g. power levels, operating conditions).

2.7. Calibration and Verification Procedure

The test setup shown in Figure 9 for studying the impacts of LTE on AMT receiver performance enables the collection of laboratory measurement data. To more fully understand the quality and limitations of the testbed data, calibrations on instrumentation and verification checks are necessary. For example, if the LTE signal needs to step by 3 dB increments, the verification and calibration process should demonstrate that the incremental changes correspond to 3 dB changes in power and provide the associated uncertainty with that value. This section outlines calibration and verification considerations to ensure the quality of the result data.

In some cases, the calibration can be completed by using an independent instrument such as a power meter, VSA, or VNA. Other verification checks on data in the communications stack layers above the physical layer (RF conditions) require examination of data sets for baseline performance. For example, a check on AMT system's nominal state requires examination of the statistical distribution of KPIs without LTE activity present. The baseline performance state under nominal conditions gives a starting point to understand system response to test variables. It is of note that this baseline response assessment is conducted with the test-setup in place as compared to an ideal signal path. This insures that the nominal/baseline condition includes inherent variability in the KPIs due to the test architecture. The list below contains items identified for the proposed test setup; others may also exist depending on the actual implementation.

1) Measurement equipment
   a) Verify all measurement equipment (e.g., spectrum analyzers, power meters, VNAs, etc.) manufacturer calibrations are up-to-date
2) Radio Frequency
   a) Reported power
      i) Check reported power values against a power meter or VSA
   b) Variable attenuators
      i) Verify attenuator performance across the frequency bands and dB setting range
   c) RF cables and RF connections
      i) Check losses, and if possible, phase behavior (e.g., through a VNA measurement), at frequency band of interest
   d) RF amplifiers
      i) Verify the performance of the amplifier at the level of operation (linearity)
3) Radio Frequency Shielding
   a) Verify that the receiver is not connecting to the AMT Tx via a leakage path
4) Output from potential interference source (e.g., LTE waveform generation)
   a) Waveform
      i) Verify total power
      ii) If surrogate waveform, verify it fits the allowable spectral mask
         (1) Verify structure – not just total power
         (2) Demodulate with an intended receiver or signal analyzer if possible to ensure the waveform transmitter integrity

b) Verify RF isolation paths
   i) to ensure the AMT waveform does not impact the LTE waveform generator
   ii) Sources of noise are appropriately accounted for

5) White Gaussian noise source (optional)
   a) Waveform
      i) Ensure bandwidth covers in-band and adjacent band signals
      ii) Ensure sufficient pseudo-random signal length is sufficient
      iii) measure the power at the receiver both with and without the noise source (without the AMT or LTE signals transmitting)

6) Data
   a) Data
      i) Determine stable collection and extraction cycle
      ii) Storage requirements on/off devices
   b) Timing
      i) Time synchronization in data sets
      ii) Determine resolution differences between devices
   c) Stability of KPIs/response variables
      i) Variability in baseline configurations
         (1) Collect data to provide statistics of baseline conditions, e.g., only one system operating – either AMT or LTE
   d) Sensitivity of KPIs to test variables
   e) Reaction time of KPIs to test variables

Documentation for calibration and verification checks in the final report should include the process and method, as well as figures and/or data which indicate the state of the setup. In the final report, tables should list the Type A or B uncertainty values associated with the elements of the setup. Uncertainty values are typically obtained from a variety of sources, including measurements in the lab, manufacturer's data sheets, and expert input. Table 2 is an example of the collection of uncertainty values from the calibration and verification process.

Table 2. Example of uncertainty values collected during the calibration and verification process.

Classification	Factor	Probability Distribution	Evaluation Type	Uncertainty (dB)
Instrumentation	LTE waveform power	Normal	B	0.4
Test setup	Calibration of setup	Normal	B	0.5
	Amplifier drift	Normal	A	0.1

2.8. Measurement Location(s)

Location to execute the test methods will be influenced by the selection of the Technical Lead and what location can be quickly, and cost effectively, scheduled to support the testing schedule.

Potential test locations being investigated include:

- Recording of radiated emissions of COTS LTE AWS-3 hardware:
    - NIST Broadband Interoperability Testbed (Boulder Labs, Boulder CO)
    - NASCTN lab (Boulder)
    - MITRE (Bedford, MA/McLean, VA)
    - Applied Physics Laboratory at Johns Hopkins University (Laurel, MD)
    - NTS (commercial facility in Longmont)
- Capture of LTE AWS-1 emissions and statistical analysis of spectrum congestion:
    - Telemetry Range Sites (Edwards AFB, CA)
    - NASA Langley Research Center, LRAS facility (Hampton VA)

3. Statistical Test Design

3.1. Overview

The basic test design methodology is explained in Appendix A. A test design based on design of experiment methodologies will be performed in a controlled laboratory environment. The test team evaluated a series of experiment design types such as full and fractional factorials, space filling, and D-Optimal split-plot designs using standard design evaluation criterion such as the distribution of test points across the test space, statistical power and confidence, optimality criteria, variance of the prediction coefficients, pairwise comparison between the factor effects, and the prediction variance vs. fraction of design space. Based on that evaluation of the candidate test designs, the team has selected a design that is referred to as a "Split-split-Plot Design." Details about this design are provided in the sections below.

3.2. Problem Scope and Test Objectives

As stated in Section 1.3, the scope of this project is to develop a calibrated, reproducible laboratory test methodology that will capture data on the behavior of AMT Rx KPIs in the presence of various power levels of adjacent band LTE activity, with calculated uncertainties. The breadth, depth, and represented conditions in the data sets shall support statistical analysis that translates laboratory results to AMT interference protection criteria and future design considerations.

Specifically, the objective of this test is to quantify the effects of various AWS-3 LTE UE emissions on an AMT receiver as a function of the factors (i.e., control variables) listed in Table 3, In other words, the analysis should establish the relationship between all factors listed in Table 3 and the KPIs, also referred to as response variables in design of experiments methodologies, a selection of which are listed in Section 2.2.

3.3. Response Variables

Section 2.2 provides a down-selected list of the KPIs that are tracked and evaluated throughout the test.

3.4. Control Variable Considerations:

- With respect to bit synch, BER measurement implies that bit synch has occurred
- Recording AMT receiver signal levels
- Recording with and without a receiver equalizer for Shaped Offset Quadrature Phase Shift Keying (SOQPSK) is very important
- Space-time coding improvements
- RSSI data

3.5. Plan for Testing

The goals of the test campaign are to

i) Determine the impact of LTE on AMT systems using a combination of sensitivity and susceptibility analysis. Test AMT sensitivity using synthesized waveforms in varied time, frequency, and power conditions and introduce a set of LTE energy recordings and then perform AMT susceptibility testing using captured LTE waveforms.

ii) Capture LTE waveforms in a laboratory setting (such as within an anechoic chamber) using consumer off-the-shelf (COTS) hardware in operational scenarios learned from part i). These captures (recordings) LTE will be used as surrogate waveforms for testing.

iii) Describe methods and help perform an observational study of in situ captures (using AMT receiver plus vector signal transceiver) to collect AWS-1 emissions. These collections will be of distant AWS-1 LTE energy and can be used as surrogate waveforms for testing and to inform AWS-3 LTE waveform selection.

Part i) is two parts, information-gathering exploratory and final LTE susceptibility to AMT measuring how a variety of signal structures affect AMT. In other words, this phase will address questions like: if -55 dBm (for instance) of white gaussian noise does measurable harm to an AMT link, how does that -55 dBm differ if the WGN energy is narrow band or frequency-hopping?

This phase will be performed in a laboratory setting using equipment connected over coaxial cables and splitters, such as in Figure 9, substituting the LTE box with a arbitrary waveform generator equipped vector signal generator. The exploratory portion injects synthesized waveforms produced from a signal generator mimicking classes of waveforms that LTE can resemble. The exploratory work will determine the AMT link's sensitivity to waveform types or classes. The same test bed will be used for injecting LTE captured waveforms to test effects on the AMT link. The LTE testing will determine an AMT link's susceptibility to LTE.

Part ii) will be a collection of LTE energy focusing on what is learned from the exploratory findings. Placing a small set of LTE UEs in a large anechoic chamber, attaching UEs to an eNB, sending realistic traffic, and collecting UE emissions with a VST. These captures can be injected into the AMT test set, portrayed in Figure 9, as an interfering source. These captures can be done in the intended AWS-3 band.

Part iii) is for both information-gathering and to serve as informing another set of interference waveforms to inject into the test set. These waveforms will be collected at the AWS-1 band using AMT architecture through its intended high-gain antenna. The waveforms collected will be in-situ and offer differing characteristics based on measurement location such as a littoral environment in close proximity to an urban environment to a desert environment with considerable distance (20 to 40 km) to a populated area. It is expected that distant LTE traffic will be more noise like in signal structure, whereas nearby LTE traffic may be more structured.

3.5.1. Near LTE Condition

From previous NASCTN testing, it was observed that a single (or "sufficiently small set") UE emits a more temporal signal with a low duty cycle. From the perspective of an AMT receiver, a temporal condition would mimic an operational scenario of a near UE (or small set of UEs). Pulsing a small set of resource blocks at a level expected from a UE near an AMT receiver is covered in this test phase.

3.5.2. Far LTE Condition

Also covered in the discovery phase is simulating several UEs at a farther setting. In the "far" scenario of LTE conditions, such as when a telemetry receiver points its antenna towards a population center that includes many UEs attached to many uncoordinated eNBs, the signal is expected to appear more noise-like.

3.6. Final Test Space Coverage (subject to change)

Table 3. Test Space Coverage

Factor	Factor Definition	Units	Type	No. Levels	Notional Levels	Change Type
A	AMT Receiver Filter	n/a	Categorical	2	Legacy, Upgrade	VHTC
B	Receiver Asset Type	n/a	Categorical	2	Fixed, Portable	HTC
C	AMT Modulation	n/a	Categorical	3	SOQPSK, ARTM CPM, SOQPSK-LDPC	ETC
D	Permissible CNIR levels for a given AMT performance	dB	Continuous	2	1-10	ETC
E	Distance (path loss) between transmitter and telemetry receivers	Km	Continuous	2	0.05-320	ETC
F	Neighboring (J-Block) LTE waveform	n/a	Categorical	4	None, W1, W2, W3	ETC

Table 3 provides a list of the controlled factors, or input variables, that could potentially influence the KPIs. Controlled factors are systematically varied throughout the test to understand their effects have on the KPIs, or response variables. The systematic combination of controlled factors serves as the basis for generating the test run matrix. Our controlled factors are of two types: continuous and categorical. Continuous factors are numeric independent variables that have an infinite number of values between any two points. Categorical factors contain a finite number of categories or groups, such as the factor levels themselves. Factor levels are the different values that a factor can take. Change Type refers to how easily the factor levels can be changed: easy-to-change (ETC), hard-to-change (HTC), or very-hard-to-change (VHTC) factors. The factors and their associated levels were selected by a group of subject matter experts and test designers.

3.7. Final AMT Testing Strategy

The initial test design structure consists of a split-split-plot design with one whole-plot (VHTC) factor and one sub-plot (HTC) factor. There are sixteen sub-plots (referred to as "Flights") with 11 runs per sub-plot. The sixteen whole plots provide adequate replication to obtain a reasonable estimate of the whole-plot factor variance. A sample complete run matrix is illustrated in the Table 5, in 6.Appendix B.

3.8. Statistical Data Analysis and Evaluation Plan

The main objectives of the analysis are: (1) to determine which of the factors listed in Table 3, influence the responses listed in Section 2.2; (2) to establish a relationship (i.e. and empirical low-order Taylor Series approximation) between the response variables and factors. The core of the statistical data analysis involves the use of techniques such as descriptive statistics, analysis of variance, analysis of covariance, and restricted maximum likelihood for regression.

4. Test Support

4.1. Coordination and Outreach

A NASCTN test brings science, outreach, and information handling components to its tests. The coordination and outreach plan for this test began during the test plan drafting stages. To expand the reach for community comment solicitation, this test plan were posted on the NASCTN website (https://www.nist.gov/communications-technology-laboratory-ctl/nasctn/projects/) and emailed to known stakeholders and interested organizations. Further distribution to their membership is encouraged. Comments were requested via a form and subsequently adjudicated. The comment period lasted for almost three weeks. After the comments were adjudicated the draft was updated. A workshop will be scheduled to discuss the updated test plan with the sponsor and affected community before test execution begins.

The NASCTN test team is interested in tracking AMT KPIs in the presence of unintended signals. These KPIs may be controlled information that an organization may not wish to share outside of NASCTN. In the case of working with controlled information, NASCTN is prepared to protect information by drafting contracts such as non-disclosure agreements (NDAs) or cooperative research and development agreements (CRADAs). Contact the NASCTN Program Manager, Dr. Melissa Midzor (Melissa.Midzor@nist.gov, 303.497.3591) to discuss implementing agreements.

To maintain impartiality and scientific quality standards, NASCTN will oversee and manage the test execution and data analysis to obtain the highest degree of trust amongst all stakeholders. The final test report will be peer reviewed and published as a NASCTN Report. The report will be provided to the sponsor of the test upon completion of the Editorial Review Board process. NASCTN will also provide an out-brief, describing test execution and results made at a time agreeable to the sponsor and key stakeholders.

4.2. Data Management

The following measures will be taken to manage data.

- Measurement data will be recorded on local media storage at the test location and will be physically removed by NASCTN personnel at the end of the measurement period.
- There are no classified or proprietary data handling concerns identified at this time.
- Measurement data will be released as an open publication to the general public after review.

4.3. Safety

Safety considerations both specific to the test location and equipment shall be reviewed and discussed with the test team by the project and technical leaders. Team members will need to demonstrate they have completed all safety training necessary to carry out the testing in the laboratory or other designated location.

4.4. Project Tasks

The following are the major tasks of the project.

Develop and Write Test Plan
External Outreach and Test Plan Review
Collect and Adjudicate Comments
Feedback Review Information to Test Plan
Conduct AMT KPI Response & KPI sensitivity Testing (Objective 1a)
Conduct waveform captures of LTE Waveforms from COTS hardware in anechoic environment
Curate catalog of LTE Waveforms (Objective 2)
Perform in-situ LTE measurements at potential sights as identified on page 16 (Objective 3)
Test Preparation / prepare synthesized test waveforms
Automated conducted test setup and Baseline Tests
Conduct AMT Susceptibility Testing (Objective 1b) to LTE waveforms
Data Analysis and Report
Describe in-situ data collection procedure / collect in-site waveform distributions at telemetry site
NASCTN Data and Report Review Process (including Director)
Issue Report

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6. Acronyms

3GPP	3rd Generation Partnership Project
AMT	Aeronautical mobile telemetry
AWS-3	3rd group of Advanced Wireless Services bands
BER	Bit Error Rate
CINR	Carrier to Interference + Noise Ratio
CIO	Chief Information Officer
CRADA	Cooperative Research and Development Agreement
DL	Down Link
DoD	Department of Defense
DOE	Design of Experiment
DUT	Device Under Test
EAFB	Edwards Air Force Base
EIIP	Equivalent Isotropic Incident Power
EIRP	Equivalent Isotropic Radiated Power
eNB	evolved UTRAN Node B or Evolved Node B
ETC	Easy to Change
EVM	Error Vector Magnitude
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
HTC	Hard to Change
IP	Internet Protocol
ITS	Institute for Telecommunication Sciences
ITU	International Telecommunications Union
KPI	Key Performance Indicators
LTE	Long Term Evolution
NASCTN	National Advanced Spectrum and Communications Test Network
NDA	Non-Disclosure Agreement
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
OFDM	Orthogonal Frequency Division Multiplexing
OoB	Out of Band
RCC	Range Commander’s Council
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
Rx	Receiver
SOQPSK	Shaped Offset Quadrature Phase Shift Keying
T&E	Test and Evaluation
Tx	Transmitter
UE	User Equipment
UL	Up Link
USB	Universal Serial Bus

UTG	UE Traffic Generator
VNA	Vector Network Analyzer
VSA	Vector Signal Analyzer
VSG	Vector Signal Generator
WGN	White Gaussian Noise

Appendix A – Design of Experiment

In general, the d*esign of experiment* (DOE) provides the techniques and methods to deal with the imperatives in the test plan. DOE is the systematic integration of well-defined and structured scientific strategies for gathering empirical knowledge about a system or process using statistical methods for planning, designing, executing, and analyzing an experiment or test. DOE-based test design is a best practice for test and evaluation (T&E).

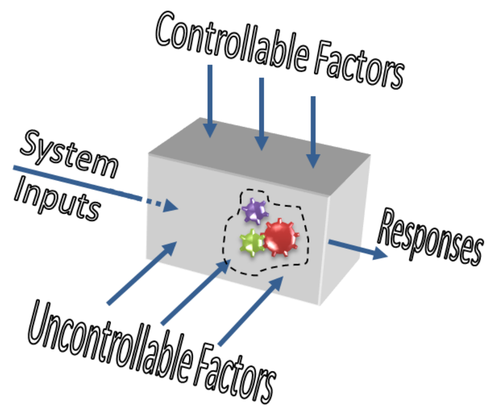

Figure 11. Design of Experiment.

As illustrated in Figure 11, DOE seeks to explain how changes in the setting of controllable factors influence the response variables, given a process and the natural variability embedded in the process, controllable factors, and uncontrollable factors. The system is represented by the gray box. Typically, the controllable factors are of interest and may influence the outcome of the experiment while the uncontrollable factors (also known as nuisance factors, tend to obscure the outcome of experiments even though there is no interest in them. Input variables become factors when they can take two or more values, called levels. In general, DOE methodologies allow for: (1) identifying the factors and interactions that influence system performance (screening); (2) defining empirical models (characterization) that could be useful for decision making and performance assessment; (3) finding factor settings that maximize or minimize the responses of interest (optimization); (4) making statistically defensible choices between options (comparison); and (5) validating system performance (validation). The relationship between the factors and the response may be partially known or unknown a priori.

DOE-based test designs leverage the amalgamation of rigorous and disciplined scientific processes and statistics into a foundational framework that helps facilitate an understanding of the tradeoffs in the risks, cost, and utility of information domains. The framework has been well established within the DOE community of practice for years and has been published in many papers and textbooks (such as [15]). That framework is leveraged into a set of desired end states in the context of the plan-design-execute-analyze paradigm as illustrated in Figure 12. The attributes of well design tests are listed in Table 4.

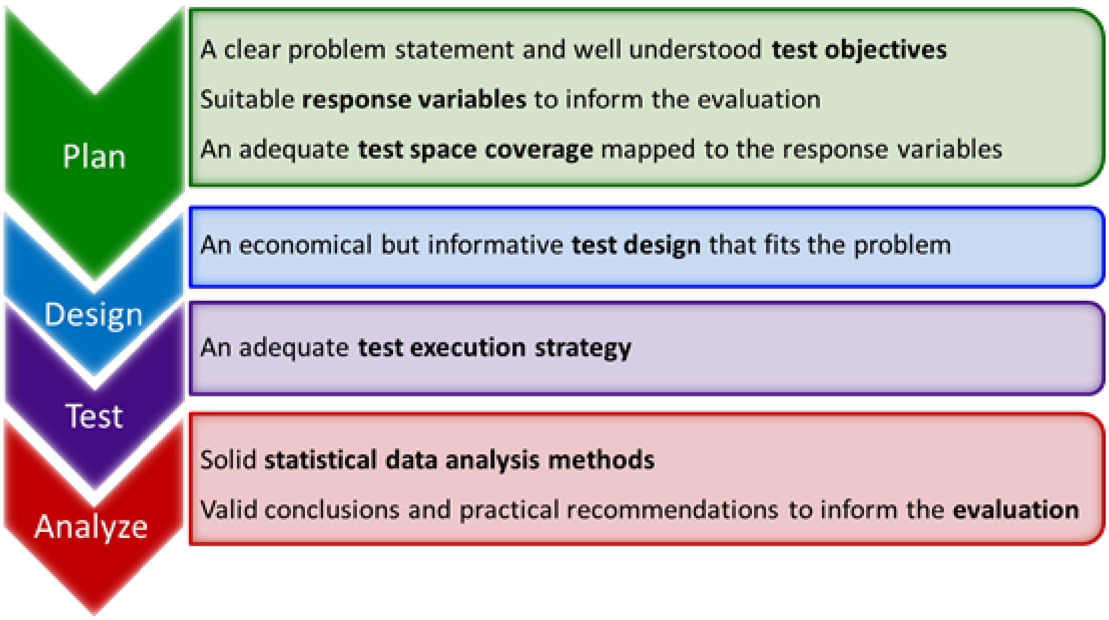

Figure 12. DOE-based Test Design Framework

Table 4. Attributes of DOE-based Test Design

Phase	Target Area	Attribute
Planning	Test Objectives	Well-defined, end-to-end, mission-oriented objectives within the scope of the decisions that will be informed
	Response Variables	Testable technical performance and mission-oriented response variables to inform the evaluations and assessments
	Test Space Coverage	Controllable and uncontrollable factors and conditions mapped to the technical and operational requirements
Design	Test Structure	DOE-based test designs that fit the problem, with good properties, and practical run matrices
Execution	Test Strategy	Sound test protocols and adequate test strategies consistent with DOE-generated run matrices
Analysis	Statistical Data Analysis	Inferential statistics, adequate assessment techniques, and standard evaluation criteria
	Evaluation	Valid conclusions and defensible information-quality products to inform decisions

Appendix B – D-Optimal Split-Split-Plot Run Matrix

Table 5. D-Optimal Split-Split-Plot Run Matrix (176-run, 16-flights)

Layout			Whole-Plot Factor	Sub-Plot Factors				
Whole-Plot Number	Sub-Plot Number (Flight No.)	Run	AMT Receiver Filter (Factor A)	Receiver Type (Factor B)	AMT Modulation (Factor C)	SINR (Factor D)	Range (Factor E)	LTE Waveform (Factor F)
1	1	1	Upgrade	Portable	SOQPSK	1	0.05	W2
1	1	2	Upgrade	Portable	ARTM CPM	1	37.27	None
1	1	3	Upgrade	Portable	ARTM CPM	10	75.71	W3
1	1	4	Upgrade	Portable	SOQPSK	10	115.14	None
1	1	5	Upgrade	Portable	SOQPSK	1	152.04	W1
1	1	6	Upgrade	Portable	PCMFM	1	160.03	W3
1	1	7	Upgrade	Portable	SOQPSK	10	187.59	W3
1	1	8	Upgrade	Portable	ARTM CPM	1	223.41	W2
1	1	9	Upgrade	Portable	ARTM CPM	10	257.66	W1
1	1	10	Upgrade	Portable	PCMFM	10	290.17	W1
1	1	11	Upgrade	Portable	PCMFM	10	320.00	W2
1	2	1	Upgrade	Portable	SOQPSK	1	0.05	None
1	2	2	Upgrade	Portable	SOQPSK	10	37.27	W2
1	2	3	Upgrade	Portable	SOQPSK	10	75.71	W1
1	2	4	Upgrade	Portable	ARTM CPM	1	115.14	W3
1	2	5	Upgrade	Portable	PCMFM	1	152.04	W1
1	2	6	Upgrade	Portable	ARTM CPM	10	160.03	None
1	2	7	Upgrade	Portable	PCMFM	1	187.59	None
1	2	8	Upgrade	Portable	SOQPSK	1	223.41	W3
1	2	9	Upgrade	Portable	ARTM CPM	10	257.66	W1
1	2	10	Upgrade	Portable	ARTM CPM	1	290.17	W2
1	2	11	Upgrade	Portable	PCMFM	10	320.00	W3
2	3	1	Legacy	Fixed	ARTM CPM	1	0.05	W2
2	3	2	Legacy	Fixed	PCMFM	10	37.27	W1
2	3	3	Legacy	Fixed	PCMFM	1	75.71	W3
2	3	4	Legacy	Fixed	SOQPSK	1	115.14	W1
2	3	5	Legacy	Fixed	ARTM CPM	1	152.04	W3
2	3	6	Legacy	Fixed	ARTM CPM	1	160.03	None
2	3	7	Legacy	Fixed	SOQPSK	10	187.59	W3
2	3	8	Legacy	Fixed	PCMFM	1	223.41	None
2	3	9	Legacy	Fixed	SOQPSK	10	257.66	W2
2	3	10	Legacy	Fixed	ARTM CPM	10	290.17	W1
2	3	11	Legacy	Fixed	SOQPSK	10	320.00	None
2	4	1	Legacy	Portable	SOQPSK	10	0.05	W1
2	4	2	Legacy	Portable	ARTM CPM	10	37.27	None
2	4	3	Legacy	Portable	SOQPSK	10	75.71	None
2	4	4	Legacy	Portable	PCMFM	10	115.14	W3
2	4	5	Legacy	Portable	PCMFM	10	152.04	W2
2	4	6	Legacy	Portable	PCMFM	10	160.03	W1
2	4	7	Legacy	Portable	PCMFM	1	187.59	None
2	4	8	Legacy	Portable	ARTM CPM	1	223.41	W3
2	4	9	Legacy	Portable	ARTM CPM	1	257.66	W2
2	4	10	Legacy	Portable	SOQPSK	1	290.17	W2
2	4	11	Legacy	Portable	SOQPSK	1	320.00	W1

Table 5 (Cont.). D-Optimal Split-Split-Plot Run Matrix (176-run, 16-flights)

Layout			Whole-Plot Factor	Sub-Plot Factors				
Whole-Plot Number	Sub-Plot Number (Flight No.)	Run	AMT Receiver Filter (Factor A)	Receiver Type (Factor B)	AMT Modulation (Factor C)	SINR (Factor D)	Range (Factor E)	LTE Waveform (Factor F)
3	5	1	Upgrade	Portable	ARTM CPM	10	0.05	W2
3	5	2	Upgrade	Portable	SOQPSK	1	37.27	None
3	5	3	Upgrade	Portable	SOQPSK	10	75.71	W3
3	5	4	Upgrade	Portable	ARTM CPM	1	115.14	W1
3	5	5	Upgrade	Portable	PCMFM	10	152.04	W2
3	5	6	Upgrade	Portable	PCMFM	10	160.03	None
3	5	7	Upgrade	Portable	SOQPSK	10	187.59	W1
3	5	8	Upgrade	Portable	ARTM CPM	10	223.41	None
3	5	9	Upgrade	Portable	SOQPSK	1	257.66	W2
3	5	10	Upgrade	Portable	PCMFM	1	290.17	W3
3	5	11	Upgrade	Portable	PCMFM	10	320.00	W1
3	6	1	Upgrade	Fixed	PCMFM	10	0.05	W2
3	6	2	Upgrade	Fixed	ARTM CPM	10	37.27	W1
3	6	3	Upgrade	Fixed	ARTM CPM	1	75.71	W3
3	6	4	Upgrade	Fixed	SOQPSK	10	115.14	W3
3	6	5	Upgrade	Fixed	SOQPSK	1	152.04	W2
3	6	6	Upgrade	Fixed	SOQPSK	10	160.03	None
3	6	7	Upgrade	Fixed	PCMFM	1	187.59	W1
3	6	8	Upgrade	Fixed	ARTM CPM	1	223.41	W2
3	6	9	Upgrade	Fixed	PCMFM	10	257.66	W3
3	6	10	Upgrade	Fixed	ARTM CPM	10	290.17	None
3	6	11	Upgrade	Fixed	SOQPSK	1	320.00	None
4	7	1	Legacy	Portable	ARTM CPM	10	0.05	W3
4	7	2	Legacy	Portable	PCMFM	1	37.27	W1
4	7	3	Legacy	Portable	PCMFM	10	75.71	W3
4	7	4	Legacy	Portable	PCMFM	1	115.14	None
4	7	5	Legacy	Portable	ARTM CPM	1	152.04	W2
4	7	6	Legacy	Portable	PCMFM	10	160.03	W2
4	7	7	Legacy	Portable	SOQPSK	10	187.59	W2
4	7	8	Legacy	Portable	SOQPSK	1	223.41	W2
4	7	9	Legacy	Portable	ARTM CPM	10	257.66	None
4	7	10	Legacy	Portable	SOQPSK	1	290.17	W3
4	7	11	Legacy	Portable	ARTM CPM	10	320.00	W1
4	8	1	Legacy	Portable	ARTM CPM	10	0.05	W3
4	8	2	Legacy	Portable	PCMFM	1	37.27	W2
4	8	3	Legacy	Portable	ARTM CPM	10	75.71	W2
4	8	4	Legacy	Portable	PCMFM	10	115.14	W3
4	8	5	Legacy	Portable	ARTM CPM	10	152.04	W1
4	8	6	Legacy	Portable	SOQPSK	10	160.03	None
4	8	7	Legacy	Portable	PCMFM	1	187.59	W3
4	8	8	Legacy	Portable	SOQPSK	10	223.41	None
4	8	9	Legacy	Portable	SOQPSK	1	257.66	W3
4	8	10	Legacy	Portable	PCMFM	1	290.17	W1
4	8	11	Legacy	Portable	ARTM CPM	1	320.00	None

Table 5 (Cont.). D-Optimal Split-Split-Plot Run Matrix (176-run, 16-flights)

Layout			Plot Factor	Factors				
Whole-Plot Number	Sub-Plot Number (Flight No.)	Run	AMT Receiver Filter (Factor A)	Receiver Type (Factor B)	AMT Modulation (Factor C)	SINR (Factor D)	Range (Factor E)	LTE Waveform (Factor F)
5	9	1	Legacy	Fixed	ARTM CPM	10	0.05	None
5	9	2	Legacy	Fixed	PCMFM	10	37.27	W2
5	9	3	Legacy	Fixed	SOQPSK	10	75.71	W1
5	9	4	Legacy	Fixed	PCMFM	1	115.14	None
5	9	5	Legacy	Fixed	PCMFM	1	152.04	W1
5	9	6	Legacy	Fixed	SOQPSK	10	160.03	W2
5	9	7	Legacy	Fixed	SOQPSK	1	187.59	W3
5	9	8	Legacy	Fixed	ARTM CPM	1	223.41	W2
5	9	9	Legacy	Fixed	ARTM CPM	10	257.66	W3
5	9	10	Legacy	Fixed	PCMFM	10	290.17	W3
5	9	11	Legacy	Fixed	ARTM CPM	1	320.00	W1
5	10	1	Legacy	Fixed	ARTM CPM	1	0.05	W3
5	10	2	Legacy	Fixed	SOQPSK	10	37.27	W3
5	10	3	Legacy	Fixed	PCMFM	1	75.71	W3
5	10	4	Legacy	Fixed	SOQPSK	1	115.14	None
5	10	5	Legacy	Fixed	PCMFM	10	152.04	None
5	10	6	Legacy	Fixed	SOQPSK	10	160.03	W1
5	10	7	Legacy	Fixed	ARTM CPM	10	187.59	W1
5	10	8	Legacy	Fixed	PCMFM	10	223.41	W2
5	10	9	Legacy	Fixed	ARTM CPM	1	257.66	None
5	10	10	Legacy	Fixed	SOQPSK	1	290.17	W2
5	10	11	Legacy	Fixed	PCMFM	1	320.00	W1
6	11	1	Upgrade	Fixed	PCMFM	1	0.05	W2
6	11	2	Upgrade	Fixed	SOQPSK	1	37.27	W3
6	11	3	Upgrade	Fixed	ARTM CPM	10	75.71	W3
6	11	4	Upgrade	Fixed	ARTM CPM	10	115.14	None
6	11	5	Upgrade	Fixed	SOQPSK	10	152.04	W2
6	11	6	Upgrade	Fixed	PCMFM	10	160.03	W1
6	11	7	Upgrade	Fixed	SOQPSK	10	187.59	W1
6	11	8	Upgrade	Fixed	PCMFM	10	223.41	W3
6	11	9	Upgrade	Fixed	SOQPSK	1	257.66	W1
6	11	10	Upgrade	Fixed	PCMFM	1	290.17	None
6	11	11	Upgrade	Fixed	ARTM CPM	1	320.00	W2
6	12	1	Upgrade	Fixed	PCMFM	10	0.05	W3
6	12	2	Upgrade	Fixed	SOQPSK	10	37.27	None
6	12	3	Upgrade	Fixed	SOQPSK	10	75.71	W2
6	12	4	Upgrade	Fixed	SOQPSK	1	115.14	W1
6	12	5	Upgrade	Fixed	PCMFM	1	152.04	W1
6	12	6	Upgrade	Fixed	SOQPSK	1	160.03	W3
6	12	7	Upgrade	Fixed	ARTM CPM	10	187.59	W2
6	12	8	Upgrade	Fixed	PCMFM	1	223.41	W2
6	12	9	Upgrade	Fixed	ARTM CPM	10	257.66	W1
6	12	10	Upgrade	Fixed	ARTM CPM	1	290.17	None
6	12	11	Upgrade	Fixed	PCMFM	10	320.00	None

Table 5 (Cont.). D-Optimal Split-Split-Plot Run Matrix (176-run, 16-flights)

Layout			Whole-Plot Factor	Sub-Plot Factors				
Whole-Plot Number	Sub-Plot Number (Flight No.)	Run	AMT Receiver Filter (Factor A)	Receiver Type (Factor B)	AMT Modulation (Factor C)	SINR (Factor D)	Range (Factor E)	LTE Waveform (Factor F)
7	13	1	Legacy	Fixed	SOQPSK	10	0.05	W3
7	13	2	Legacy	Fixed	ARTM CPM	1	37.27	W1
7	13	3	Legacy	Fixed	PCMFM	10	75.71	W1
7	13	4	Legacy	Fixed	ARTM CPM	10	115.14	None
7	13	5	Legacy	Fixed	PCMFM	1	152.04	W3
7	13	6	Legacy	Fixed	PCMFM	1	160.03	W2
7	13	7	Legacy	Fixed	SOQPSK	1	187.59	None
7	13	8	Legacy	Fixed	PCMFM	10	223.41	None
7	13	9	Legacy	Fixed	ARTM CPM	10	257.66	W3
7	13	10	Legacy	Fixed	SOQPSK	1	290.17	W2
7	13	11	Legacy	Fixed	ARTM CPM	10	320.00	W2
7	14	1	Legacy	Portable	ARTM CPM	10	0.05	W2
7	14	2	Legacy	Portable	PCMFM	10	37.27	W1
7	14	3	Legacy	Portable	SOQPSK	1	75.71	None
7	14	4	Legacy	Portable	PCMFM	10	115.14	None
7	14	5	Legacy	Portable	ARTM CPM	1	152.04	None
7	14	6	Legacy	Portable	SOQPSK	10	160.03	W3
7	14	7	Legacy	Portable	PCMFM	1	187.59	W2
7	14	8	Legacy	Portable	SOQPSK	1	223.41	W1
7	14	9	Legacy	Portable	ARTM CPM	1	257.66	W3
7	14	10	Legacy	Portable	SOQPSK	10	290.17	W2
7	14	11	Legacy	Portable	ARTM CPM	1	320.00	W1
8	15	1	Upgrade	Portable	SOQPSK	10	0.05	W2
8	15	2	Upgrade	Portable	SOQPSK	1	37.27	None
8	15	3	Upgrade	Portable	ARTM CPM	10	75.71	W3
8	15	4	Upgrade	Portable	SOQPSK	1	115.14	W3
8	15	5	Upgrade	Portable	SOQPSK	10	152.04	W1
8	15	6	Upgrade	Portable	PCMFM	10	160.03	None
8	15	7	Upgrade	Portable	ARTM CPM	1	187.59	None
8	15	8	Upgrade	Portable	PCMFM	1	223.41	W1
8	15	9	Upgrade	Portable	PCMFM	1	257.66	W2
8	15	10	Upgrade	Portable	ARTM CPM	1	290.17	W1
8	15	11	Upgrade	Portable	ARTM CPM	10	320.00	W2
8	16	1	Upgrade	Fixed	SOQPSK	10	0.05	W3
8	16	2	Upgrade	Fixed	SOQPSK	1	37.27	W2
8	16	3	Upgrade	Fixed	PCMFM	1	75.71	W3
8	16	4	Upgrade	Fixed	PCMFM	10	115.14	W2
8	16	5	Upgrade	Fixed	PCMFM	1	152.04	None
8	16	6	Upgrade	Fixed	SOQPSK	10	160.03	None
8	16	7	Upgrade	Fixed	ARTM CPM	1	187.59	W3
8	16	8	Upgrade	Fixed	PCMFM	10	223.41	W1
8	16	9	Upgrade	Fixed	ARTM CPM	10	257.66	W2
8	16	10	Upgrade	Fixed	SOQPSK	10	290.17	W1
8	16	11	Upgrade	Fixed	ARTM CPM	1	320.00	W1

Appendix C – Test Plan Compared to Existing Test Methods

Related test methods exist for telemetry, particularly the Range Commanders Council IRIG 118 Volume 2, Chapter 4.22 TEST: Receiver Adjacent Channel Interference and Chapter 7.5 TEST: Demodulator Adjacent Channel Interference Test [16]. The methods in [16] connect the telemetry system in operational mode and monitor BER[8]. A key consideration is that the BER is set to 10^{-5} with injected white Gaussian noise when no interference is present. Then attenuators are adjusted to maintain that BER value as the interference is introduced.

This test plan proposes an expanded method to (i) include multiple LTE UE emissions across power levels and traffic types, (ii) track additional telemetry response variables, and (iii) exercise the telemetry link across more operational and control settings. This expansion on the IRIG 118 method should reveal a sensitivity of the response variables to the presence and variations of interference. The most sensitive response variables can then be down-selected to KPIs to best measure the effects of various interference conditions from the adjacent band.

Table 6. comparison of control factors and response variables (subject to change after pre-test activities)

	IRIG 118, 7.5		
	Response Variables		Control factors
1	BER	A	# interferers (1 or 2)
		B	modulation method
		C	receiver filters
		D	bit rates
		E	power levels
		F	frequency spacing
		G	demodulator characteristics

	NASCTN TEST PLAN		
	Response Variables		Control factors
1	BER	A	LTE aggregate signal over multi-UE space
2	RSSI	B	AMT modulation
3	CINR	C	Receiver equalizer
4	Errored bit-seconds	D	Antenna G/T
5	Space-time coding improvements	E	AMT SINR
6	EVM	F	Link range AMT TX/RX
		G	Frequency spacing
		H	Dish diameter (converted to gain)
		I	AMT TX antenna elevation angle
		j	AMT TX power

Table 6 summarizes the differences in telemetry link conditions and values recorded. The table does not show the multiple runs that will be recorded to produce the statistical power needed to uncover the uncontrolled covariates and quantify the error bars of the measurands. Having more KPIs to track allows for a test space which creates an "area" of effects shown in Figure 13. An area of results will give the results a richer understanding of effects and their repercussions.

[8] Other response variables are not considered, but may lend more insight in to effects of the LTE energy

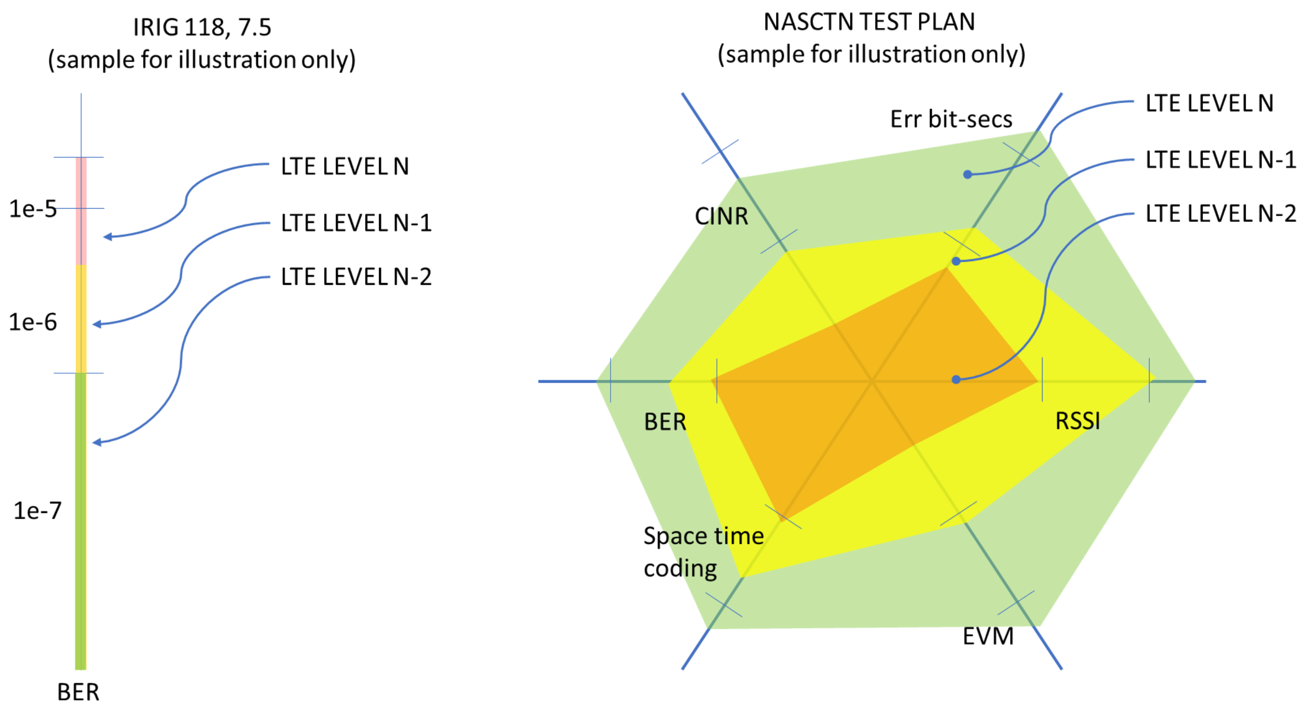

Figure 13. LTE interference effects across one KPI versus multiple KPIs

The IRIG methods uses pre-biasing the setup to a BER and then add interference in the adjacent band. The waterfall behavior of the receiver BER is either derived or measured assuming Gaussian or approximately Gaussian noise. There is no reason to assume that the adjacent band signal would add to the noise in a Gaussian manner, and thus assume the extrapolated performance would closely track the waterfall plot based on Gaussian noise. If a test takes 10 hours unattended using automation versus one hour attended without automation, with more assumptions, and with a higher uncertainty, it is not obvious the latter method is a better approach. Considering that automation of the test process should be used to capture sufficient data points for a robust statistical analysis, reduce potential human error, and improve repeatability, the benefits of saving time are not immediately obvious.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

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1. REPORT DATE *(DD-MM-YYYY)*

2. REPORT TYPE
Plan

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
LTE Impacts on AMT Test and Metrology Test Plan

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Mark Lofquist, Dan Jablonski, Ari Cortes, William F. Young. Duncan McGillivray, Melissa Midzor, Keith Hartley, Irena Stevens

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Institute of Standards and Technology (NIST)
Communications Technology Laboratory, NASCTN Program Office
325 Broadway
Boulder, CO 80305

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
412th Test Engineering Group
Spectrum Relocation Program
307 E. Popson Avenue, Suite 204
Edwards AFB, CA 93524

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release. Distribution Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS
NASCTN, LTE, RF Testing, Metrology.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Melissa Midzor
					19b. TELEPHONE NUMBER *(Include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	None	35	(303) 497-3591