NASCTN Plan [P-16-x]
NTIA Technical Report TR-[xx]-[xxx]
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AWS-3 Out of Band Emissions Measurements Test and Metrology Phase II Test Plan

Arthur Webster	NTIA/ITS
NASCTN Test Master	
Sheryl Genco	NIST/CTL
NASCTN Project Manager	
Jason Coder	NIST/CTL
Brent Bedford	NTIA/ITS
Adam Wunderlich	NIST/CTL
Jean-Aicard Fabien	NTIA/ITS
Frank Sanders	NTIA/ITS
John Ladbury	NIST/CTL
Azizollah Kord	NIST/CTL

October 11, 2016

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.

The U.S. Department of Commerce's National Institute of Standards and Technology (NIST) and National Telecommunications and Information Administration (NTIA) established the Center for Advanced Communications (CAC) in Boulder, Colorado, to address, among other challenges, the increasing need for spectrum sharing testing and evaluation capabilities to meet national needs. As part of CAC's mission to provide a single focal point for engaging both industry and other government agencies on advanced communication technologies, including testing, validation, and conformity assessment, NASCTN was formed under the umbrella of the CAC. NIST hosts the NASCTN capability at the Department of Commerce Boulder Laboratories in Boulder, Colorado.

NASCTN is a membership organization under a charter agreement. Members

- Make available, in accordance with their organization's rules policies and regulations, engineering capabilities and test facilities, with typical consideration for cost.
- Coordinate their efforts to identify, develop and test spectrum sharing ideas, concepts and technology to support the goal of advancing more efficient and effective spectrum sharing.
- Make available information related to spectrum sharing, considering requirements for the protection of intellectual property, national security, and other organizational controls, and, to the maximum extent possible, allow the publication of NASCTN test results.
- Ensure all spectrum sharing efforts are identified to other interested members.

Current charter members are:

- National Telecommunications and Information Administration (NTIA)
- National Institute of Standards and Technology (NIST)
- Department of Defense Chief Information Officer (DoD CIO)

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Preface

The National Advanced Spectrum and Communications Test Network (NASCTN) provides a neutral forum for addressing spectrum-sharing challenges in an effort to accelerate the deployment of wireless technologies among commercial and federal users. NASCTN was created in 2015 and is a joint effort among the National Institute of Standards and Technology (NIST), the National Telecommunications and Information Administration (NTIA), and the United States Department of Defense (DoD).

NASCTN's mission is to provide 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 is a function within the Center for Advanced Communications, a joint research effort of the NTIA and NIST.

Representatives from Edwards Air Force Base submitted a proposal to NASCTN to measure out of band emissions (OOBE) from LTE eNB and UE in the United States Advanced Wireless Service (AWS)-3 frequency band into adjacent L and S frequency band aeronautical mobile telemetry (AMT) systems. NASCTN formed a team to examine the proposal and discuss it with the proposer. The team decided to recommend that the proposal be adopted as a NASCTN project. The Center for Advanced Communications co-directors considered the recommendation and decided to create a new NASCTN project.

A Test Plan development team, composed of experienced engineers and other professionals, was formed. While working on the details of the test plan, the team performed investigations and some simplified measurements in LTE Band 3 with commercially available equipment to guide the team's decisions. 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 proposed LTE activities to AMT activities in the adjacent L and S Bands. NASCTN will solicit comments about the test plan from the engineering community within federal and non-federal groups and entities.

Contents

List of Figures

List of Tables

Executive Summary

The purpose of this NASCTN project is to establish a test methodology and measure the out of band emissions (OOBE) from LTE user equipment (UE) and evolved NodeB base station (eNodeB or eNB) activities in the United States AWS-3 frequency band into the adjacent L and S frequency bands utilized by aeronautical mobile telemetry (AMT) systems. Phase I of this project is the development of a test methodology for measuring out of band emissions from AWS-3 equipment. Phase II will involve the actual measurement of out of band emissions from AWS-3 UE and eNB.

During Phase I, the NASCTN team performed initial investigations and measurements to inform and develop this test plan and methodology for conducting out of band emission measurements on LTE UE and eNodeBs that will operate in the United States AWS-3 band. Due to the unavailability of commercial equipment in the AWS-3 band at the beginning of this project, the Phase I measurements were performed on 3GPP Band 3 equipment. That effort informed the development of this test plan.

Two measurement setups and procedures are described in this test plan. The first is a setup and procedure to measure the emissions of a UE. Depending on the UE under test, either conducted emissions measurements or coupled emission measurements are performed. A base station emulator used to control the desired emissions from the UE. A spectrum analyzer is used in a stepped measurement system to measure the isolated UE emissions with peak and average detectors. The measurement bandwidths are varied from 100 kHz to 3 MHz and the number of UE transmitted resource blocks are varied from 5 to 50. This measurement procedure is expected to produce over 100 dB of measurement range in the result.

The second is a setup and procedure to measure the emissions of an eNB. Conducted emissions measurements are performed in a simpler measurement setup since the eNB does not require a second transceiver to be present for the test. A spectrum analyzer is used in a stepped measurement system to measure the isolated UE emissions with peak and average detectors. The measurement bandwidths are varied from 100 kHz to 3 MHz and the number of UE transmitted resource blocks are varied from 5 to 50. This measurement procedure is expected to produce over 110 dB of measurement range in the result.

The Appendix to this test plan provides measurement results from the OOBE testing done on the 3GPP Band 3 equipment. Those results informed and validated some of the test plan’s methods. The objective of Phase I was not to produce final spectrum measurements but to do simplified spectrum measurements from which to make observations and develop the test plan. None of the spectra shown in the appendix should be used to draw conclusions or make decisions[1].

[1] The purpose of the Phase II Test Plan is to define measurement methods for OOBE in AWS-3 bands (1755–1780 MHZ uplink and 2155–2180 downlink). Because AWS-3 (3GPP Band 66) is newly licensed, equipment was not available for testing. To determine the test methodologies (subject of Phase I), 3GPP Band 3 (1710–1785 MHz uplink and 1805–1880 MHz downlink) equipment was used. See the Appendix for more details.

NASCTN will next seek public comment on this test plan. In Phase II, the final test plan will be executed and measurements made on actual AWS-3 equipment. Detailed and informative spectra will be published at the end of Phase II.

AWS 3 Out of Band Emissions Measurements Test and Metrology Phase II Test Plan

Arthur Webster,[2] Sheryl Genco,[3] Jason Coder,[3] Brent Bedford,[2] Adam Wunderlich,[3] Jean-Aicard Fabien,[2] Frank Sanders,[3] John Ladbury,[3] Azizollah Kord[3]

Abstract: Wide dynamic range emission measurements of LTE mobile phones (user equipment, or UEs) and base station hardware (eNodeBs) that will share spectrum with telemetry links in the newly available AWS-3 band U.S. (designated Band 66 by 3GPP) are needed. A test plan for measuring out of band emissions is presented that ensures objective, repeatable, and reproducible measurement results. The measurement method is outlined and demonstrated for Band 3 hardware (note that the uplink for Bands 3 and 66 overlap). The test plan describes emission measurements that will be performed by NASCTN on a variety of LTE UEs and eNodeBs that will be deployed in the AWS-3 band. These measurements will provide data on out of band emissions from AWS-3 equipment. The data may inform interference analyses for band sharing studies, including frequency and distance separation parameters between LTE hardware and telemetry receivers, to preclude harmful interference from UEs to telemetry links when the AWS-3 band is eventually shared by these systems.

Keywords: Band sharing; band sharing analysis; interference analysis; eNodeB (eNB); emission spectrum; telemetry links; user equipment (UE); AWS-3; 1755-1780 MHz, 2155-2185 MHz; Band 66; aeronautical mobile telemetry (AMT); out of band emissions (OOBE); spectrum measurements.

1. Introduction

The Federal Communications Commission (FCC) has auctioned off and is issuing licenses for the introduction of new radio systems into the 1755–1780 MHz (uplink) and 2155–2180 MHz (downlink) portion of radio spectrum in the United States (commonly referred to as AWS-3 or Band 66). Out of band emissions (OOBE) from LTE devices have the potential to impact operation of co-located and adjacent-band aeronautical mobile telemetry (AMT) systems that operate in the 1780–1850 MHz (L Band) and 2200–2395 MHz (S Band) frequency bands. This part of the frequency spectrum is depicted in Figure 1.

[2] The authors are with the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U.S. Department of Commerce, Boulder, CO 80305.
[3] The authors are with the Communications Technology Laboratory, National Institute of Standards and Technology, U.S. Department of Commerce, Boulder, CO 80305.

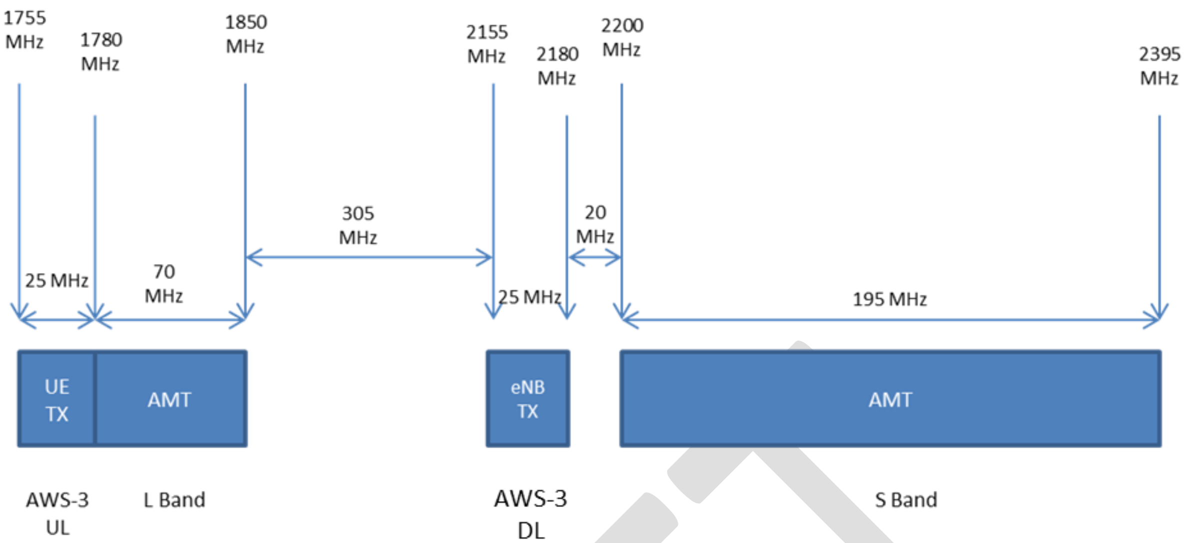

Figure 1. Frequency bands of interest for this test.

A joint team of National Telecommunications and Information Administration (NTIA) and National Institute of Standards and Technology (NIST) engineers are collaborating within the National Advanced Spectrum and Communications Test Network (NASCTN) to develop a test and metrology plan suitable to ensure transparent, and reproducible measurements of AWS-3 OOBEs. This NASCTN team has performed initial investigations and measurements to inform the development of a test plan to use for conducting OOBE measurements on LTE User Equipment (UEs) and eNodeBs (eNBs) operating in the AWS-3 band (1755-1780 MHz uplink and 2155-2180 MHz downlink). The initial investigations and measurements are referred to as Phase I. In Phase I, the test plan was developed that is to be used for Phase II. Because the commercial equipment in the AWS-3 band was not available at the start of this effort, the Phase I measurements were done on existing NIST-owned 3GPP Band 3 (1710-1785 MHz uplink and 1805-1880 MHz downlink) equipment. The Phase II test plan will be executed on AWS-3 equipment.

Spectrum sharing studies require interference analyses that are based on detailed, wide dynamic range measurements of emissions from individual transmitters that are to share spectrum with other systems. Such measurements show the rate of roll-off of transmitted emissions as a function of off-tuning from transmitter center frequencies, e.g., that a transmitter's emission levels might be reduced by 85 dB relative to the power at the fundamental when a receiver is off-tuned from the fundamental.

It is sometimes suggested that emission measurements are not needed because it can be assumed that transmitters operate at their required emission mask limits. This assumption is nearly always false. Transmitter out of band (OOB) and spurious emissions are usually substantially lower than emission mask limits, often by tens of decibels. Interference studies that assume that transmitter emissions are as high as emission mask limits will therefore overestimate the power levels of most transmitters' OOB and spurious emissions. As a result, required frequency and distance separations needed for compatible operations between systems will also be overestimated. The only way to avoid such overestimates is to accurately measure the OOB and spurious emission levels of transmitters.

Regarding the new spectrum sharing that will soon begin in the 1755–1780 MHz spectrum, the incumbent systems are air-to-ground telemetry links that operate at U.S. flight-test ranges. These links use high-gain antennas typically pointed at elevation angles approaching 0 degrees due to the long slant ranges supported between the test platforms and ground stations to track airborne platforms carrying telemetry transmitters. The ground-based telemetry antennas feed the airborne platforms' signals into ground-based telemetry receivers for recording and analysis. The new wireless broadband systems anticipated to be introduced into 1.7 GHz spectrum will almost certainly be LTE networks consisting of user devices (UEs) and base stations (eNodeBs).

Spectrum sharing analyses need to be performed to determined how much off-tuning (number of megahertz) and distance separation (number of kilometers) are needed between transmitters and telemetry receiver stations to avoid harmful interference to the telemetry receivers. To complete these studies, detailed, wide dynamic range emission spectrum measurements of the soon-to-be-deployed AWS-3 LTE transmitters need to be performed.

Interference analyses often require emission spectrum measurements with a dynamic range of 100 dB or more. Currently available measurement instrumentation often does not achieve such wide dynamic ranges. This includes swept-frequency and high-speed time-domain sampling systems. To overcome this limitation and achieve dynamic ranges of as much as 120 dB in OOBE measurements, a measurement system with the characteristics described below needs to be used. These measurements go beyond the standard 3GPP measurements as documented in 3GPP TS 36.101 [7] and 3GPP TS 36.121 [8].

Figure 2 shows how the measurements described in this plan can be used in the overall spectrum sharing analyses for mobile-to-telemetry interference scenarios.

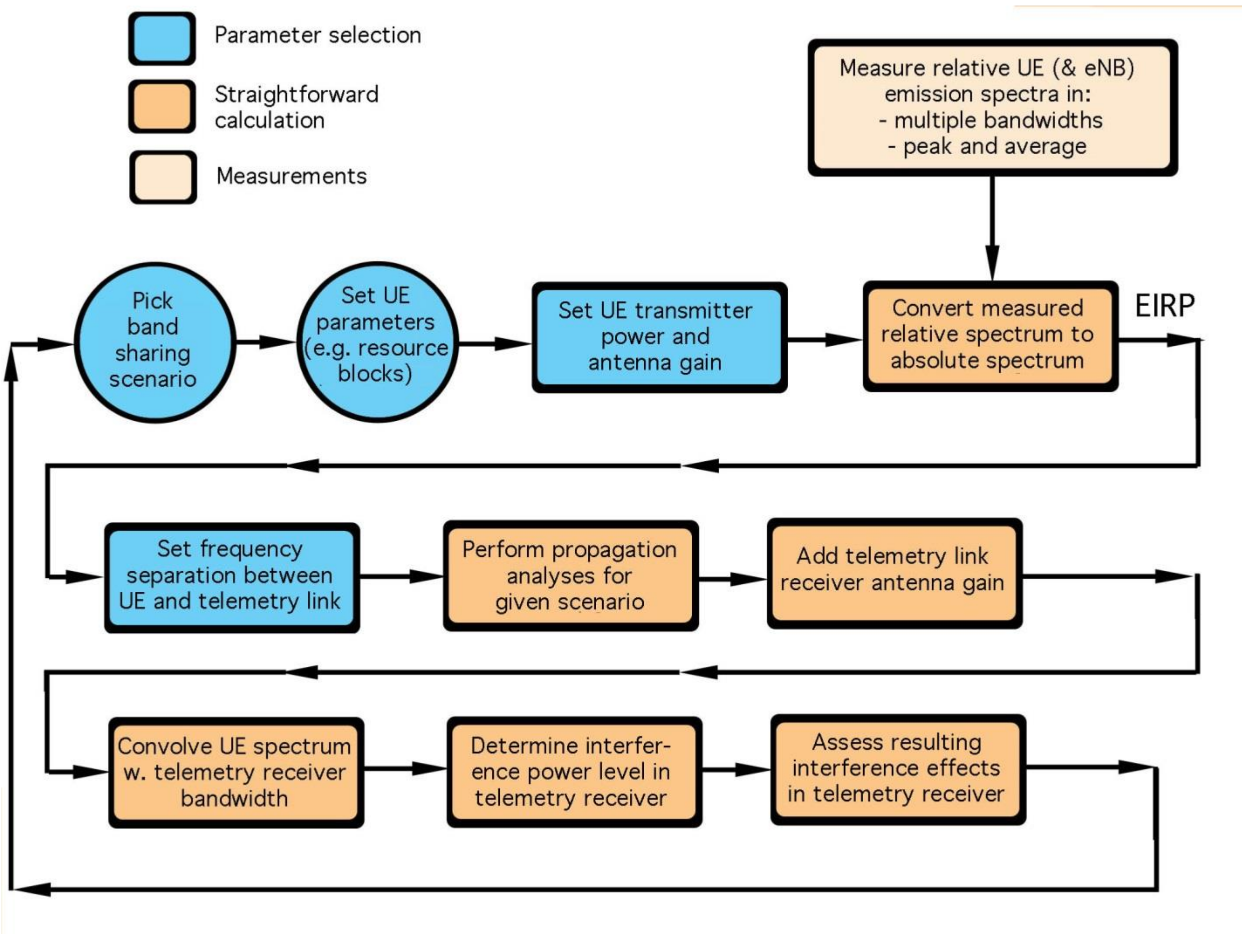

Figure 2. How emission spectrum measurements will be used in AWS-3 band sharing analysis studies.

The measurement system requires a radio frequency (RF) front end with three major components: a variable RF attenuator, a tunable bandpass filter, and a low-noise amplifier (LNA). The RF attenuator extends the dynamic range of the measurement system, the bandpass filter rejects high-power signals when the measurement system is off-tuned from the transmitter fundamental frequency, and the LNA provides a low measurement system noise figure (high sensitivity to weak signals – typical in interference measurements) in low-power portions of the transmitter emission spectrum.

The final output of these OOBE measurements will be a set of emissions data for commonly deployed hardware that demonstrates the type of emissions that may be observed in the band. These emissions will be measured as close to the device as possible, so additional analysis will be required to account for the propagation environment and telemetry receiver characteristics.

1.1. Objectives

The objective is to develop a test plan to provide measured data showing the typical emissions from LTE UE and macro-cell eNodeB devices that will be operating in the AWS-3 band. This document presents a test plan for achieving this objective, along with preliminary data supporting some of the test plan's recommendations.

1.2. Phase I Summary

During the initial planning, the test plan development team foresaw a need to determine how to configure the devices under test (DUTs) and how to configure a measurement system that will collect the emission spectra of those devices. Determining this involves research into how to configure the units and how they function under various conditions. Additional research was needed to determine the measurement system configurations needed to collect the required emissions data while the DUTs were operating in various parameters and operational modes. This need was met through some initial simplified measurements and observations, referred to as Phase I. As the goal of Phase I was to demonstrate configurations of DUTs and measurement hardware, only one UE and one eNodeB were measured.

The goal of Phase I was not to produce final spectrum measurements but to do simplified spectrum measurements from which to make observations and to learn. None of the spectra shown in this report should be used to draw conclusions or make decisions. More detailed and informative spectra are expected to be shown in a report to be published at the end of Phase II, when actual AWS-3 hardware has been measured. The results of the measurements and observations from Phase I are presented in Appendix A.

The Phase I emission spectrum measurements were performed on Band 3 hardware deployed in a laboratory setting. The measurement system was connected to the UE and eNodeB (eNB) via hardlines[4] whenever possible. When hardline connections were not possible, short-range (several cm) radiated paths were used between a small horn and the UE in an anechoic chamber. For all of the Phase I testing, the UEs and the eNB were operated at their maximum output power levels.

For each test case, the DUT's emission spectrum was measured in peak and average detection modes in bandwidths of 100 kHz, 300 kHz, 1 MHz, and 3 MHz (1 MHz will be the reference measurement bandwidth for all measurements). Emission spectra were measured as a function of the number of resource blocks (RBs) in use by the UE. The eNB spectrum was measured for three tuned frequencies: the bottom, middle, and top of the operational band.

All measured emission spectra are reported in terms of power relative to the power measured at the transmitters' center frequencies (f_0). These relative-power, normalized emission spectra will be used in larger spectrum compatibility studies as shown in Figure 2.

Phase I measurement results are shown in Figures 3 to 6. The OOBE mask is generated for the AWS 3 frequencies using the FCC equation for emission masks. In general, the Phase I measurements show that UE and eNodeB emissions fall off rapidly outside the assigned frequency band.

[4] Testing via hardline will provide the worst case emission.

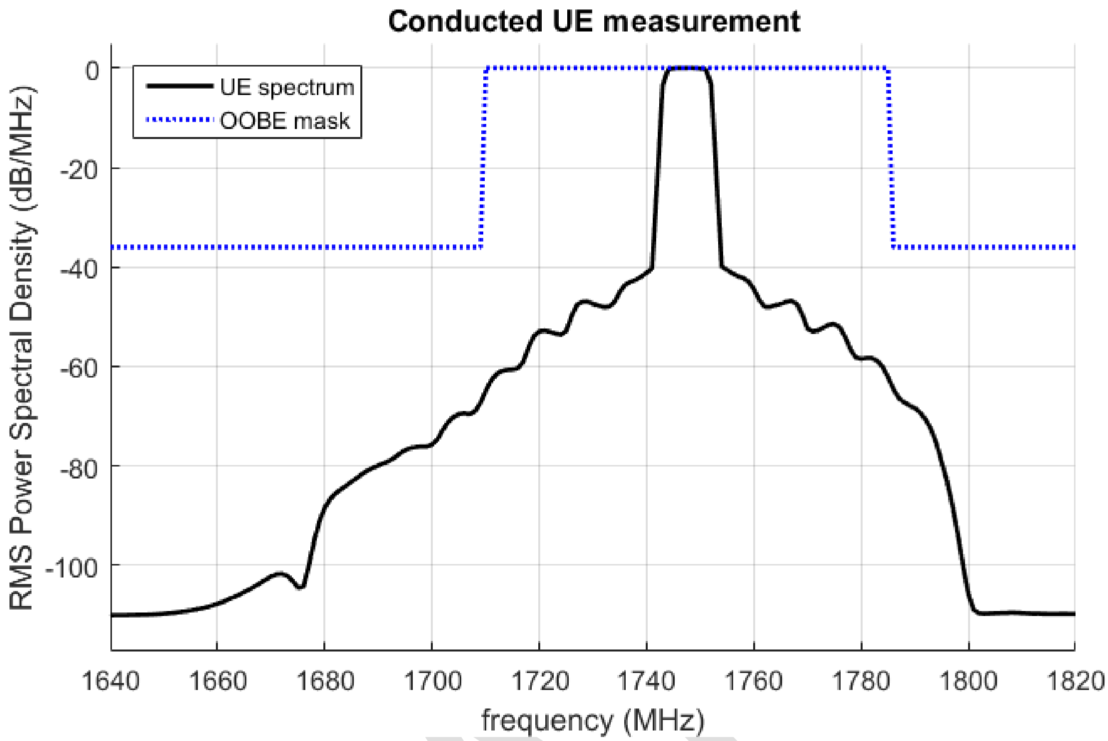

Figure 3. Conducted UE emission spectrum measurement. UE was operated at maximum power with all resource blocks occupied. The mask shown is representative of the FCC's allowable emissions mask.

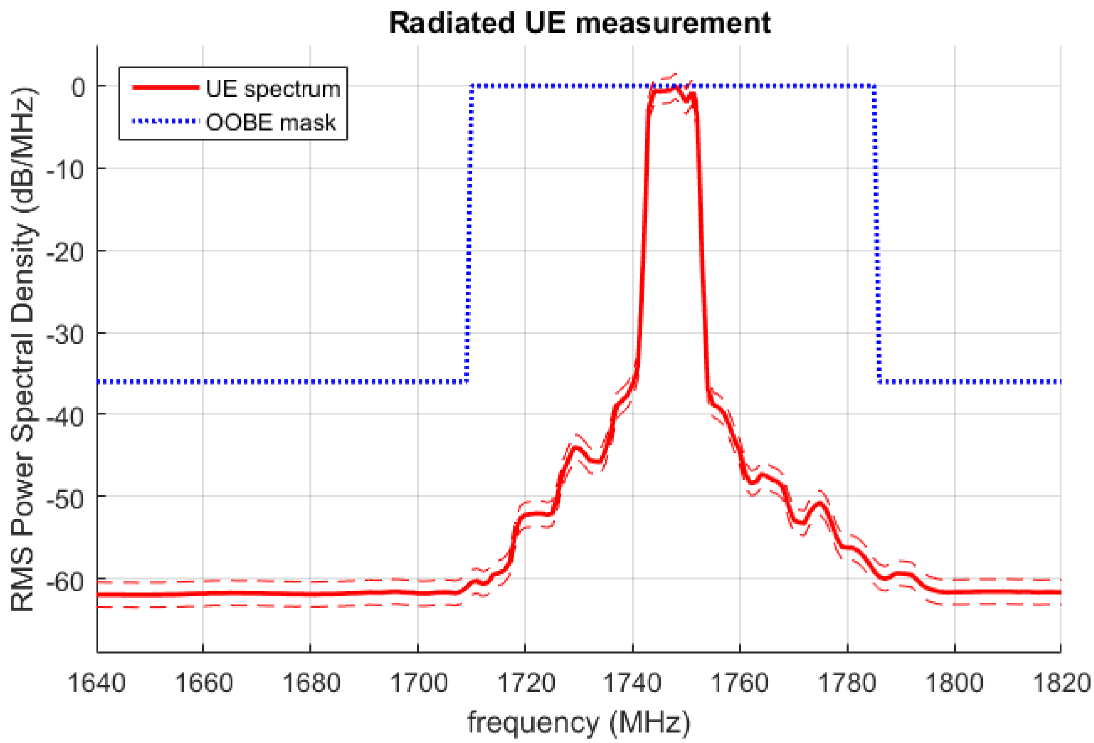

Figure 4. Radiated UE emission spectrum measurement. UE was operated at maximum power with all resource blocks occupied. The mask shown is representative of the FCC's allowable emissions mask.

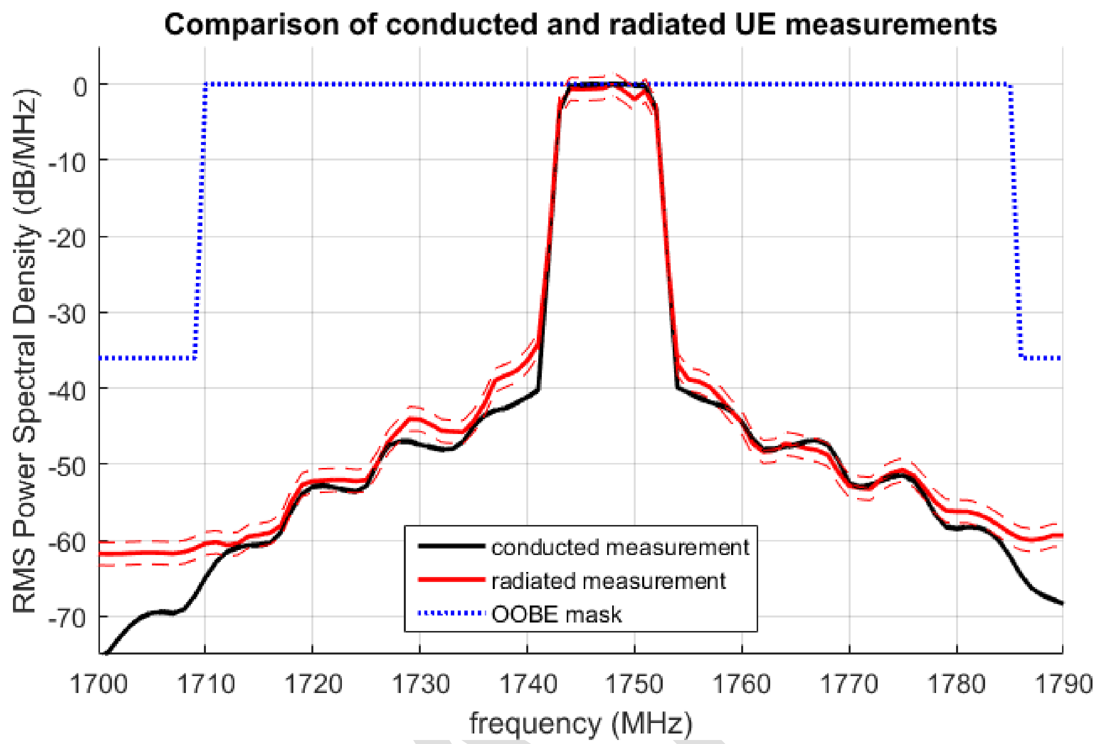

Figure 5. Comparison of conducted and radiated UE spectrum measurements. The mask shown is representative of the FCC's allowable emissions mask.

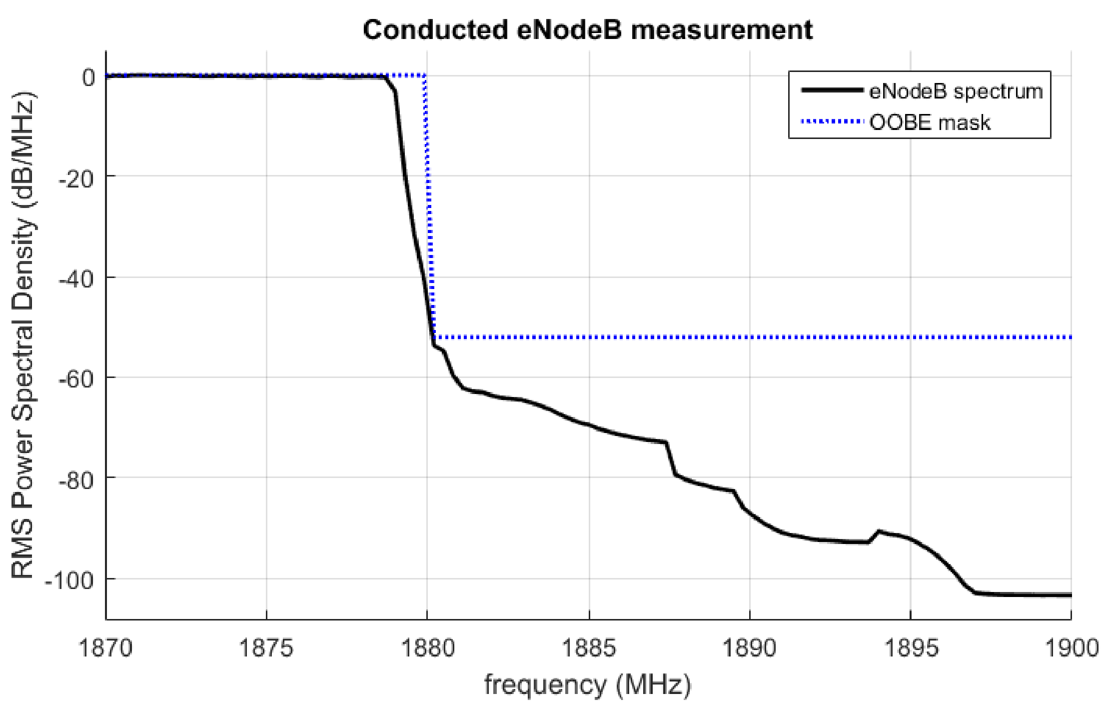

Figure 6. eNodeB conducted emission spectrum measurement. Transmitter operated at maximum power. The mask shown is representative of the FCC's allowable emissions mask.

1.3. Phase II Summary

Phase II measurements will be performed in the same manner as Phase I measurements. The difference will be that the Phase II measurements will be performed on equipment that will be deployed in the AWS-3 band.

2. Phase II DUTs

As has been discussed in earlier sections, Phase I testing involved the use of Band 3 equipment. During Phase II, actual AWS-3 hardware will be required. However, it is impractical to test all AWS-3 UEs and eNodeBs deployed in the marketplace. Therefore, a subset of deployed equipment must be selected.

During Phase I, two different Band 3 UEs were used. These were selected because they were easily available, worked in Band 3, and most importantly, provided access to their RF ports. An eNodeB was examined to demonstrate the proposed test method. This eNodeB was a macro-cell design and was deployed in late 2014.

2.1. UEs

An examination of existing deployments in the current U.S. LTE bands reveals three categories of UE types: mobile phones (commonly referred to as "UEs"), tablets, and consumer premise equipment (CPE). Examples of CPE are nano/pico/femto-cell base stations that may be deployed inside a dwelling for the purpose of repeating ("boosting") the LTE signal, and LTE routers that serve as a Wi-Fi access point and then convert the traffic to LTE.

According to a study done by Ericsson [2], smartphones constitute about 75% of the North American UE deployments. Given this, the NASCTN team decided not to measure the emissions from devices other than smartphones.

To select from all available UEs, we examined which UEs were most commonly sold in the U.S. (for any band/network). From the list of the most commonly sold UEs, we suggest selecting the top five and performing emissions measurements on them. Counterpoint Research [3] conducts a quarterly survey of the most commonly sold UEs by surveying mass market retailers and distributors. The disadvantage of this study is that it does not include sales through wireless carriers. Therefore, we make the assumption that the most popular phones sold through mass-market retailers are very similar (if not identical) to those from carriers. The top five list generated from [3] is:

1. Apple iPhone 6
2. Apple iPhone 6 Plus
3. Samsung Galaxy S6
4. Samsung Galaxy S6 Edge
5. Xiaomi Redmi 2

The first and second, and third and fourth UEs on this list are nearly identical to each other. The main difference being the display type and physical size of the UE. It is very likely that they have exactly the same RF chipsets, and thus will have very similar emissions. To augment the list, we include the sixth and seventh most popular UEs:

1. Apple iPhone 6 or 6 Plus (#2)

3. Samsung Galaxy S6 or S6 Edge (#4)

5. Xiaomi Redmi 2

6. Samsung Galaxy Note 4

7. Apple iPhone 5S

The disadvantage of each of these UEs is that their conducted RF ports are not accessible for conducted RF emissions measurements. Therefore, only coupled/radiated measurements are possible. The coupled/radiated measurement method is further discussed in Section 5.

2.2. eNodeB (Base Station) Hardware

For the purposes of the Phase I and II emissions measurements, we are only considering macro-cell eNodeBs. There will almost certainly be small cell deployments in the AWS-3 band, but they will all be lower power (e.g., <1 W) and most will be deployed indoors. Short of one being deployed in the immediate vicinity of an AMT system, their emissions are not expected to be of significant concern.

Though there are significantly fewer models of eNodeBs than there are UEs, it is still not practical to test all of the available models. The most popular UE manufacturers are (in no order): Nokia, Alacatel-Lucent (now owned by Nokia), Ericsson, Motorola, and Huawei. There are no market sales data available to identify which models or manufacturers are the most popular. In Phase II, an attempt can be made to obtain an eNodeB from each of these vendors.

By design, all macro-cell eNodeBs will give access to their RF ports. For Phase II measurements, the conducted method described in Section 7 will be used.

3. Measurement Equipment

3.1. RF Front End/Preselector[5]

The overall measurement technique is based on the stepped-measurement approach described in the best practices NTIA report [4]. Although [4] describes the technique as applied to measurements of radar emission spectra, the same technique works equally well for LTE-type emissions, as described for a 3.5 GHz LTE hotspot in [5].

Interference analyses often require emission spectrum measurements with a dynamic range of 100 dB or more. Available measurement instrumentation does not achieve such wide dynamic ranges. This includes swept-frequency and high-speed time-domain sampling systems. To overcome this limitation and achieve dynamic ranges of as much as 130 dB in emission measurements, a measurement system with the characteristics described in [4] needs to be used. As shown in Figure 7, the heart of this approach lies in the use of a radio frequency (RF) front end with three major components: a variable RF attenuator, a tunable bandpass filter, and a low-noise amplifier (LNA). The RF attenuator extends the dynamic range of the measurement system, the bandpass filter rejects high-power radio power when the measurement system is off-tuned from the radio fundamental frequency, and the LNA provides a low measurement system noise figure (high sensitivity to weak signals) in low-power portions of the radar emission spectrum.

[5] Note that this test plan uses the terms “RF Front End” and “Preselector” almost synonymously. The Preselector is a function and component of the RF Front End and consists, in the current case, of a tunable YIG Bandpass filter.

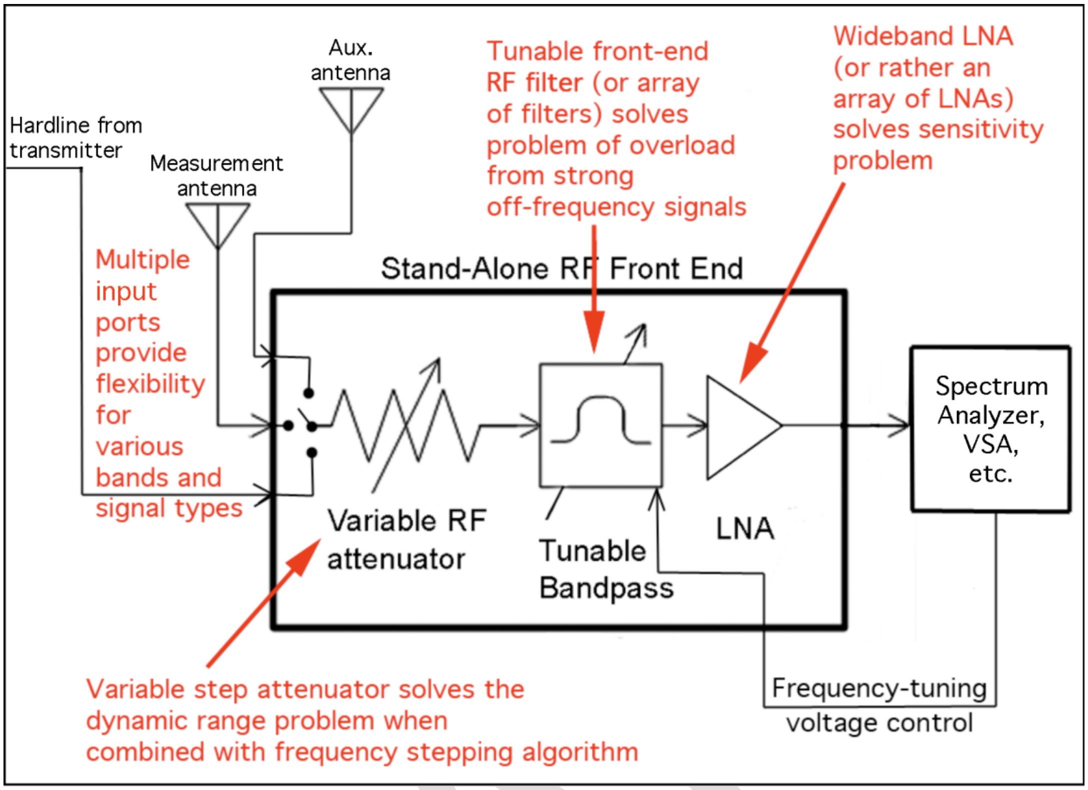

Figure 7. Block diagram of RF front end needed for wide dynamic range spectrum measurements.

The key to operation of the measurement system is to step across the emission spectrum one frequency at a time. Stepping means tuning the measurement system to a single frequency and then waiting long enough at that frequency for the transmitter (in this case an LTE system) to provide a statistically representative number of samples from which a root mean square (RMS) average power on that frequency may be computed. For LTE transmitters this interval has been found empirically to be 0.5 seconds or longer. During Phase II, the exact dwell time will be determined during the measurement and may be affected by the time needed for a peak measurement. When a measurement has been completed at a tuned frequency, the measurement system is tuned (stepped) to the next frequency to be measured. The frequency interval between tuning steps is usually equal to the resolution bandwidth of the measurement system. An additional measurement will be done with the frequency interval equal to the equivalent noise bandwidth of the smallest resolution bandwidth filter.

The stepped-frequency measurement process is described in detail in [4] for radars. For LTE measurements, this process is adapted as follows. Instead of running the spectrum analyzer in peak detection mode, the measurement system is operated in a sample-detection mode. In sampling mode, power levels are sampled randomly, and recorded, for the entire step interval. At the end of step interval, the peak and RMS power levels of those samples are computed, and those peak and RMS power levels are plotted as data points in the resulting measured spectra. This peak and RMS measurement process is repeated at each frequency step in the spectrum.

This stepped measurement process is repeated at each frequency step in the spectrum. For these LTE measurements, the measured spectra will be collected with both peak and RMS detection. The RMS spectrum points will be measured as the average of 1001 sample-detected points collected over an interval at each measured frequency step. The peak-detected point will be taken as the maximum measured power level (peak detected) during the interval.

Because stepped-frequency emission spectra are measured a single frequency at a time, the amount of attenuation invoked at the RF front end can be gradually adjusted as the measurement frequency steps progress across the spectrum. Zero attenuation is used in the lowest-power parts of the spectrum, maximum attenuation is used at the transmitter’s center frequency and intermediate amounts of attenuation are used at points in between. If a measurement system has 60 dB of instantaneous dynamic range and a 70 dB step attenuator is built into the RF front end, the total measurement dynamic range can be as much as (60 dB + 70 dB) = 130 dB.

3.2. Circulators

Circulators are multi-port RF devices that permit power to flow in certain directions with low loss but which prevent the back-flow of power toward the point of origin along those same paths. Circulators are commonly used in radar RF front ends to 1) permit power to flow from the high-power transmitter to the antenna while preventing that same power from flowing to the radar receiver at deleterious levels, and to 2) allow echo power from distant radar targets to flow backward from the antenna to the receiver with minimal loss.

In the UE emission spectrum measurement system a pair of three-port circulators will allow the base station emulator (R&S CMW-500, working as if it were an eNB) to communicate bi-directionally with the UE under test, while maintaining a degree of isolation (about 20 dB) between the CMW-500 and the spectrum measurement system.

3.3. Spectrum Analyzer

The spectrum analyzer used in these measurements will likely be an Agilent (now Keysight Technologies) E4440A. However, any similar spectrum analyzer can be used. The E4440A is a high performance digital machine. A block diagram of the E4440A is shown in Figure 8.

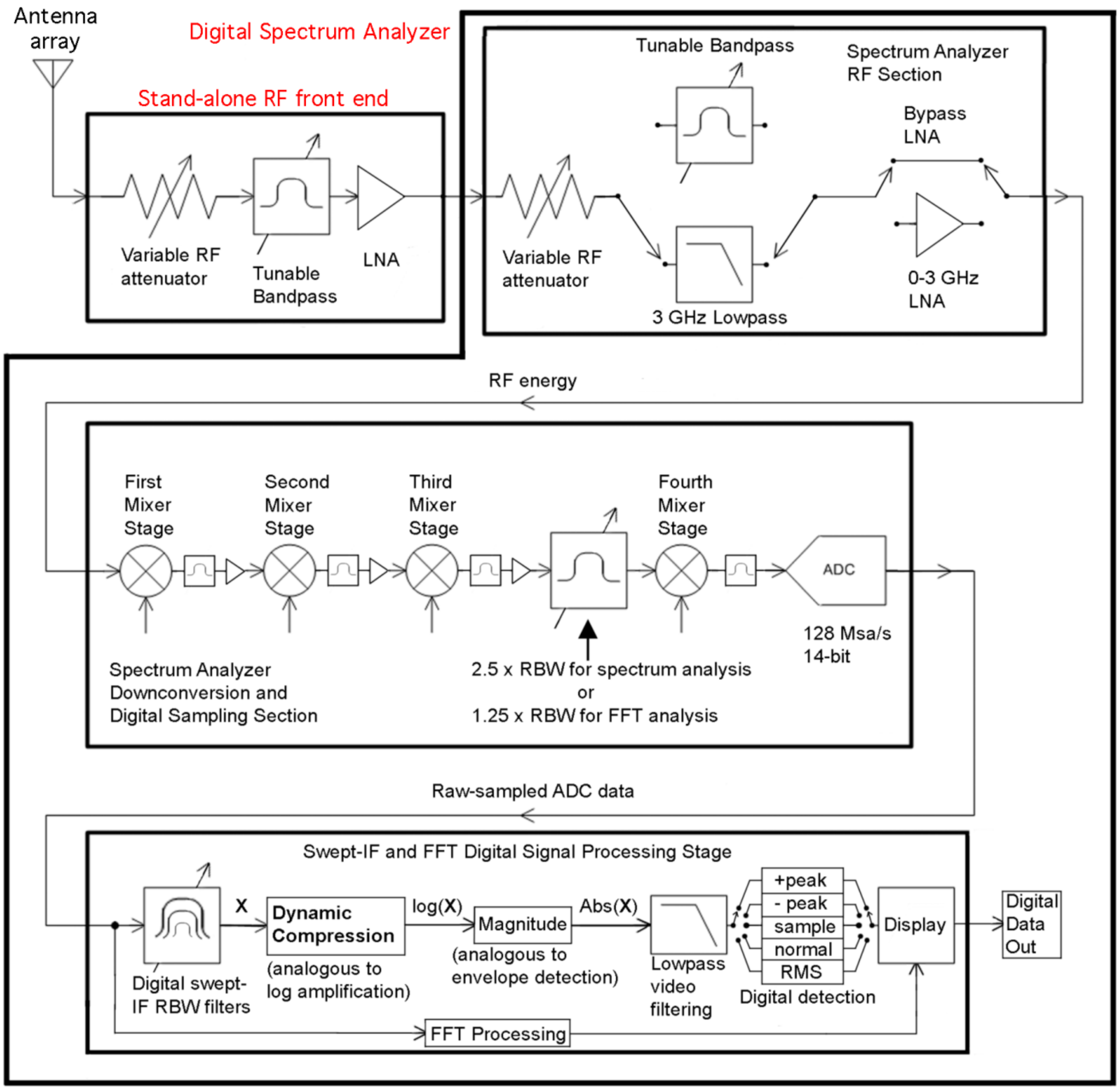

Figure 8. Block diagram of the E4440A digital spectrum analyzer with a stand-alone RF front end, as used for the UE and eNB spectrum measurements.

3.4. eNodeB (Base Station) Emulator

UEs will not operate unless they are in communication with eNodeB controllers. It is impractical to set up actual eNodeB stations for this purpose. So, eNodeB emulators are used instead. One solution is a base station emulator from Rohde and Schwarz, the CMW-500. The CMW-500 is used for communications design verification, feature testing and certification of user equipment (e.g., smartphones and dongles). The CMW-500 is capable of emulating all protocol layers: RF, physical, MAC, RRC, PDCP and IP. In Phase I and II testing, the CMW-500, is used to setup the smartphone to transmit in the carrier frequency and bandwidth of interest in order to measure OOBE. The CMW-500 is used to set the UE transmit power level and uses grants to control the resource blocks that the smartphone will transmit within the bandwidth of interest.

4. UE Measurement Setup

Figure 9 shows a block diagram of the UE measurement system. The specialized custom RF front end has been built by NTIA, but could be replicated with similar components. The UE devices being measured will use OFDM modulation and will be frequency domain duplexed (FDD) with their controller. The controller will be a Rohde & Schwartz CMW-500 running as an evolved Node B (eNodeB).[6] The CMW-500 parameters during the emission measurements are shown in Table 1.

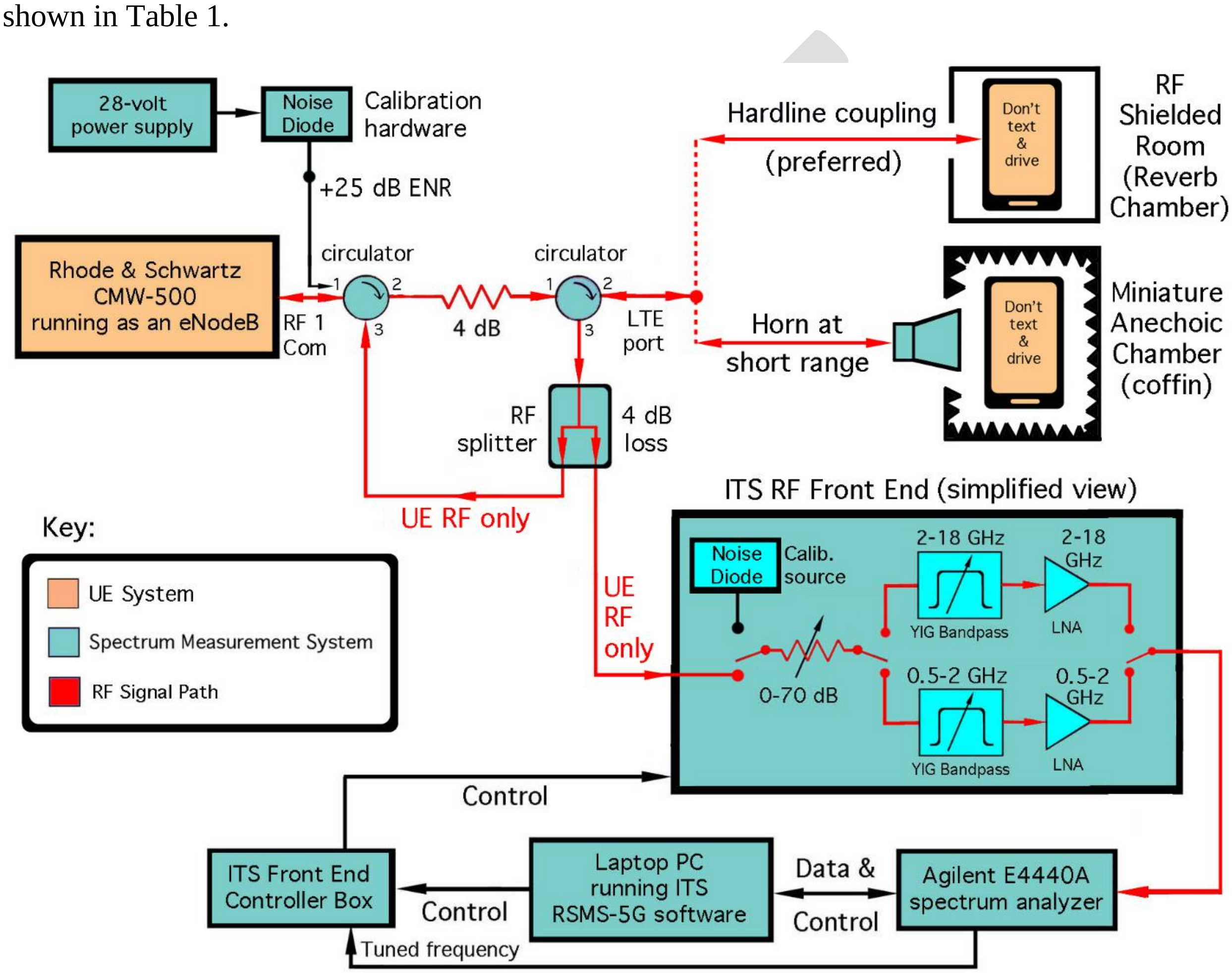

Figure 9. Block diagram of the UE emission spectrum measurement system.

To isolate the UE signal from the CMW-500 eNodeB signal for the spectrum measurement, the measurement system will use a pair of directional RF circulators that will be inserted between the UE and the eNodeB as shown in Figure 9. The circulators will provide about 20 dB of decoupling. The CMW-500 will also be operated at the lowest possible power level that still allows control of the each UE being measured. These expedients (RF circulators and minimal

[6] A Rohde and Schwartz CMW-500 operating in its eNodeB mode.

CMW-500 power) will keep the CMW-500 emissions from contaminating the UE emission spectrum measurement results.

The UE and eNodeB signals will thus be forced to run in a loop between the two LTE units, with the UE signal on one side of the loop and the eNodeB signal on the loop's other side. The measurement system takes the UE signal from an RF splitter on the UE side of the loop. The splitter has 4 dB of insertion loss; a 4 dB attenuator will be inserted between the circulators to ensure balanced RF path loss on both sides of the circulator loop. For the measurement system shown above, the system noise figure from the input to the RF front end would be approximately 8 dB. The gain of the measurement system would be approximately 24 dB.

Table 1. Operating parameters of the R&S CMW-500 during UE spectrum measurements.

UE Parameter	Parameter Value
Duplexing	Frequency Division (FDD)
RF Modulation	Quadrature Phase Shift Keying (QPSK)
Operating Radio Band	AWS 3 (1775 MHz)
Commanded Full Cell Bandwidth	10.0 MHz (with 9 MHz actually occupied when 50 RBs were running)
Measured Total Output Power at Antenna Port	+20.5 dBm (measured with an external power meter across full LTE bandwidth of 9 MHz)
Resource Block (RB) Energy Per Resource Element (EPRE)	-100.0 dBm/15 kHz (indicated by eNodeB)
Full Cell Power	-72.2 dBm (indicated by eNodeB)
Physical Uplink Shared Channel (PUSCH) Open Loop	+23.0 dBm (indicated by eNodeB)
PUSCH Closed Loop	+23.0 dBm (indicated by eNodeB)
Switching	Packet
State	Radio Resource Control (RRC)
Transfer Block Size Index (TBSI) (Downlink)	9
TBSI (Uplink)	6
Start Resource Block	0
Downlink Throughput (50 RBs)	4.795 Mbit/sec
Uplink Throughput (50 RBs)	2.064 Mbit/sec
Protocol	Internet Protocol Version 4
Antenna Gain	See main body text

As shown in Figure 9, the preferred method of connecting the UEs to the measurement system will be via hardline connections on the phone bodies. This can be a mechanically difficult process, but is possible for some UEs. For some UEs, however, no hardline connection will be possible. In this case, the UEs will be measured with a small horn antenna in a mini-anechoic chamber.

Whatever the method used for non-hardline connections, the measurement engineers will move the couplers around enough to identify the physical placement of the coupling antenna, relative to the UE, where maximum power is coupled into the measurement system. This is important because the more power that gets into the measurement system, the more dynamic range will be obtained in the spectrum measurement. In all cases, the relative placement of the UE and the coupler will be recorded (including photographically) to document the placement of the units during the measurements.

5. UE Measurement Procedure

All measurements will be performed on UEs with the UE power having been maximized by running the CMW-500 eNB communication at the lowest possible power level. (UE power will be maximized by turning down CMW-500 power until the UE loses communication, and then bringing CMW-500 power back up by 3 dB.) Table 2 lists the measurements to be performed on each UE.

The relative offsets in measured power between a transmitter’s fundamental frequency and its OOBE will vary as a function of the resolution bandwidth and measurement detector mode. The amount of this variation is ultimately determined by the modulation of the transmitter’s emissions. For noise-like transmitter modulations that are root mean square (RMS) detected this variation will go as 10log(RBW), meaning that the power convolved in the RBW is directly proportional to the width of the RBW. For pulsed transmitter emissions this variation goes to its other extremum, 20log(RBW), if the emission is peak-detected. For various other modulations and measurement detectors the coefficient of the variation goes as some value between these extremes, i.e., the variation is between 10 and 20. In order to characterize this variation in OOBE relative to power at their fundamental frequencies for the transmitters in this study, the transmitters’ emissions need to be measured across a range of RBWs.

This variation in RBWs during the measurements allows the coefficient of the OOBE and spurious-to-fundamental power variation (always somewhere between 10 and 20) to be determined with certainty. With this variation known, the measurement results can be extrapolated to victim receivers with any given bandwidth, even if victim receiver bandwidths do not necessarily correspond to any actual measurement bandwidth used in this study.

As noted above, the dynamic range of each UE emission spectrum measurement will be 100 dB or more. Each measurement’s frequency range will be determined by this dynamic range. Based on Phase I measurement results, each UE spectrum measurement will be about 200 MHz wide.[7]

Table 2. Measurement set for each UE.

Bandwidth	Detector	Resource Blocks
100 kHz	RMS average	Full Set (50)
300 kHz	RMS average	Full Set (50)
1 MHz	RMS average	Full Set (50)
3 MHz	RMS average	Full Set (50)
100 kHz	Positive Peak	Full Set (50)

[7] The 100 db dynamic range of the spectrum measurements produces emission spectra that are about 200 MHz wide.

Bandwidth	Detector	Resource Blocks
300 kHz	Positive Peak	Full Set (50)
1 MHz	Positive Peak	Full Set (50)
3 MHz	Positive Peak	Full Set (50)
1 MHz	RMS	Half Set (25)
1 MHz	RMS	Quarter Set (12)
1 MHz	RMS	1/10 Set (5)
1 MHz	Positive Peak	Half Set (25)
1 MHz	Positive Peak	Quarter Set (12)
1 MHz	Positive Peak	1/10 Set (5)

The data set for each UE is described in Table 2. All data will be provided in a digital format. Emission spectra will be normalized to 0 dB at f_0 in a 1 MHz resolution bandwidth.

The stepped-frequency measurement technique for collecting emission spectra provides a time-domain collection at each measurement step. Each measurement frequency step for all collected emission spectra will consist of 1001 data points in the time domain. All of these points will be recorded. For each spectrum that is measured, time domain data consisting of 1001 points at each measured frequency step will be recorded and provided to the sponsor. These data will, like the spectrum data, be provided in a digital format for additional processing by the recipient.

For UEs where the coupled radiated method is used, the coupler should be physically scanned around the UE to determine the location where the energy coupled into the measurement system is the highest.

6. eNodeB Measurement Setup

Figure 10 shows the setup for the eNB measurements. The measurement system will be essentially the same as, though somewhat simpler than, the UE setup. The system is simplified because the eNB can be operated stand-alone (unlike the UEs), without an associated radio to force it to operate.

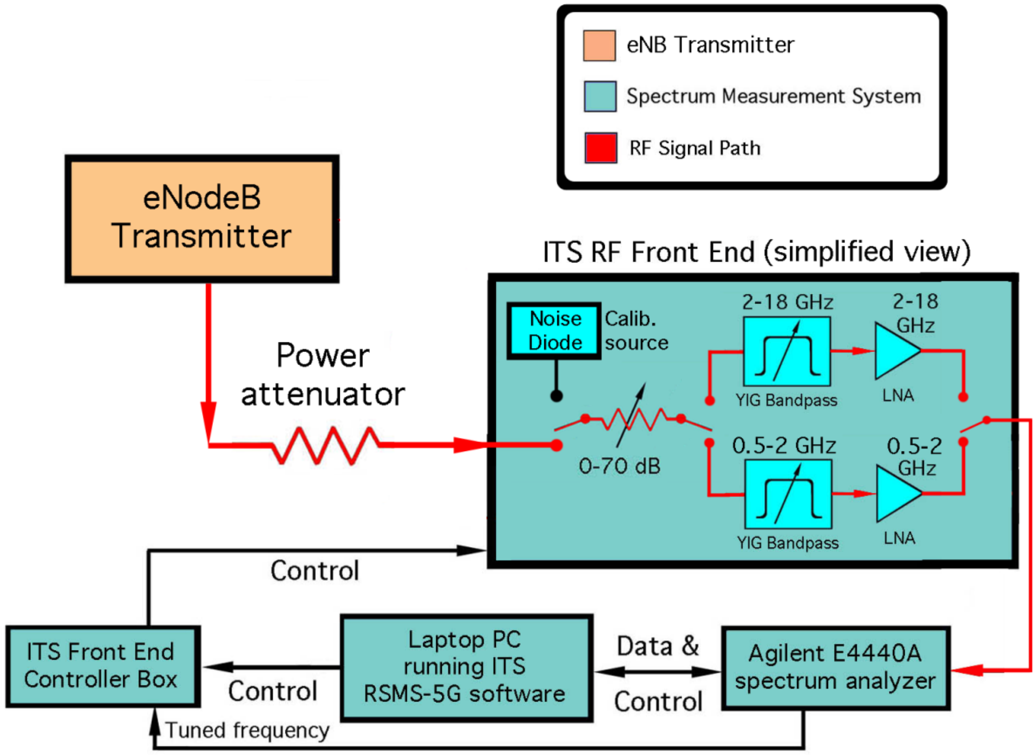

Figure 10. Block diagram of the eNB spectrum measurement system.

7. eNodeB Measurement Procedure

Phase I eNB emission spectrum measurements have shown that the measured power of these spectra can change by 80 dB or more within just a few megahertz of tuned spectrum. (This drop-off is likely achieved by a combination of excellent modulation control and high-quality eNB transmitter output filtering.) This steep change, while good for spectrum engineering, does cause a problem for emission spectrum measurements.

The problem is that the center-frequency (f_0) power from the transmitter can still be received in the measurement system, through the front-end yttrium-iron-garnet (YIG) filter, even when the measurement system is *not* tuned to f_0; the YIG has a finite, non-zero bandwidth. For the NTIA measurement system, the YIG bandwidth is on the order of 25 MHz (although it varies with tuned frequency). This non-zero characteristic means that, if the transmitter's power change with frequency is steep enough, it will still put enough power into the front end through the YIG to either overload the front end LNA or else overload the downstream spectrum analyzer IF stage when measurements are being performed close to, but not actually on, f_0.

This problem could be solved by adding attenuation in the RF front end. But adding attenuation will put the transmitter's OOB power on the tuned frequency of the measurement system below the measurement system's noise floor. So, either the measurement system attenuation is kept low enough to allow the transmitter's power on the measurement frequency to be seen, but concomitantly causing the transmitter's f_0 power to overload the measurement system, or else the attenuation is increased enough to eliminate the overload condition while causing the transmitter power on the measurement system's tuned frequency to be lost below the measurement system's noise floor. Under this condition the available dynamic range for the measurement system goes from a nominal 100+ dB to zero dB. This is the spectrum measurement coffin corner problem.

The coffin corner occurs because the spectrum being measured changes steeply, relative to the width of the RF front-end YIG filter. Ideally the YIG could be made narrower, but that is not physically possible. The YIG can, however, be *effectively* made narrower on an ad-hoc basis relative to its frequency separation from f_0. The way to do this is to *not* center-tune the YIG to the tuned frequency of the measurement system. Instead the YIG is off-tuned as much as possible from the measurement system's tuned frequency. This off-tuning approach is shown graphically in Figure 11.

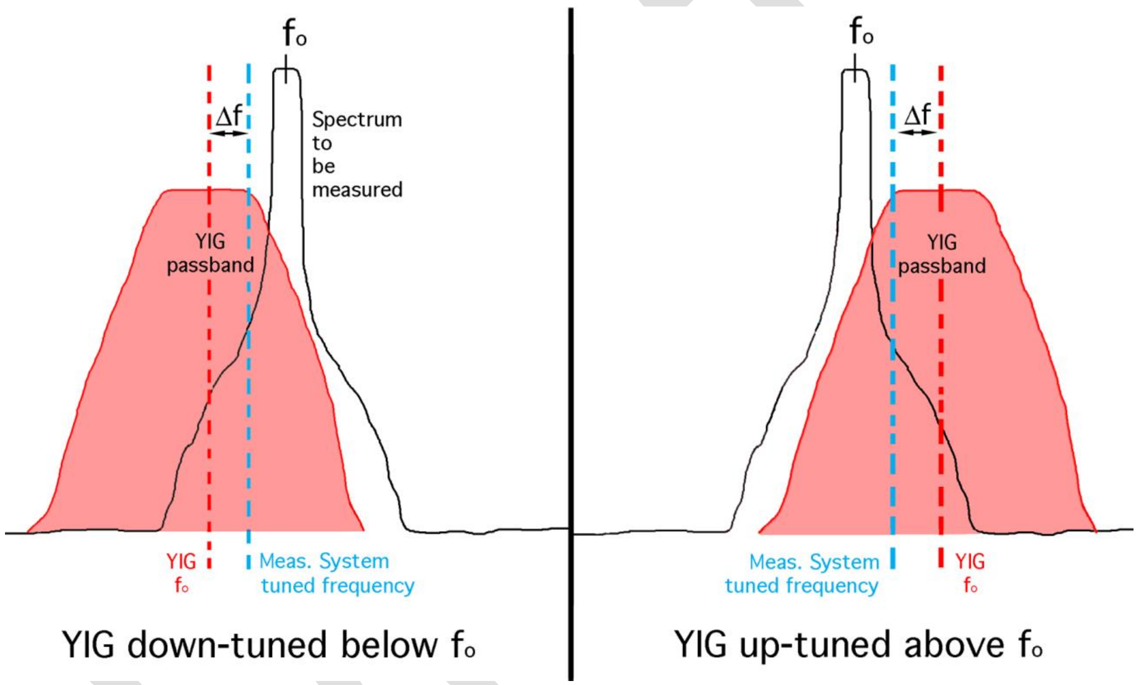

Figure 11. YIG off-tuning technique that will be used for wide dynamic range eNB emission spectrum measurements. The YIG center is offset (Δf) from the measurement system's tuned frequency up to the limit of the YIG's 3-dB roll-off points, half of the YIG's flat passband width.

The more the YIG can be off-tuned, the better for solving the coffin corner problem. In practice, the off-tuning is limited by the eventual roll-off of the YIG's passband shape. The off-tuning is performed up to the 3 dB points in the filter's rejection curve. As shown in Figure 11, the YIG off-tuning is downward when the transmitter's spectrum is being measured below f_0, and is upward for the transmitter's spectrum above f_0.

Sometimes the spectrum is so steeply changing that even off-tuning of the YIG does not completely solve the problem. But off-tuning of the YIG will always greatly reduce the number of frequency points where the coffin corner occurs, usually reducing the number of such points to either zero or else just a few on either side of f_0. YIG off-tuning will be performed for the eNB measurements, and will be done for UE measurements if the coffin corner problem should occur for any of them.

The eNB emission spectra will be measured with the transmitter running at full power and a power attenuator on its output to prevent burn-out of the measurement system. eNB emission data that will be collected are shown in Table 3.

The dynamic range of each UE emission spectrum measurement will be about 120 dB. This dynamic range will determine the measurement's frequency range. Based on Phase I measurement results, the eNB spectrum measurement will be about 300 MHz wide. The results of these Phase I tests can be found in Appendix Sections A.2.3 and A.3.3.

Table 3. Measurement set for the eNB.

Bandwidth	Detector	Resource Blocks	Comments
100 kHz	RMS average	Full set (50)	eNB tuned to center of band
300 kHz	RMS average	Full set (50)	eNB tuned to center of band
1 MHz	RMS average	Full set (50)	eNB tuned to center of band
3 MHz	RMS average	Full set (50)	eNB tuned to center of band
100 kHz	Positive peak	Full set (50)	eNB tuned to center of band
300 kHz	Positive peak	Full set (50)	eNB tuned to center of band
1 MHz	Positive peak	Full set (50)	eNB tuned to center of band
3 MHz	Positive peak	Full set (50)	eNB tuned to center of band
1 MHz	RMS	Full set (50)	eNB tuned to *bottom* of band
1 MHz	RMS	Full set (50)	eNB tuned to *top* of band
1 MHz	RMS	Half set (25)	eNB tuned to center of band
1 MHz	RMS	Quarter set (12)	eNB tuned to center of band
1 MHz	RMS	1/10 set (5)	eNB tuned to center of band
1 MHz	Positive peak	Half set (25)	eNB tuned to center of band
1 MHz	Positive peak	Quarter set (12)	eNB tuned to center of band
1 MHz	Positive peak	1/10 set (5)	eNB tuned to center of band

8. Calibration Procedure

The measurement system will be calibrated with noise diodes. The basic approach is classic Y-factor, in which the noise diode is turned on at the front end of the measurement system at a known excess noise ratio[8] (ENR), say +25 dB, and the power from the diode is measured for a set of frequencies across the expected frequency range of the ensuing measurements. Then the diode is turned off and the output of the measurement system is measured is measured a second time for each of those calibration frequencies. The power difference between diode = ON and diode = OFF is then compared for each of those frequencies. Given that the noise diode's ENR is

[8] ENR is relative to *kTB*, where *k* is Boltzmann's constant (1.38^-23 J/K/Hz), *T* is the ambient temperature and *B* is the bandwidth in which the noise is observed or measured.

already accurately known from separate, NIST-traceable calibrations of the component, the noise figure and gain of the measurement system at each calibration frequency is now known. Those calibration factors are stored in a frequency-dependent look-up table. They are retrieved and applied (that is, the measurement system's gain corrections are applied) to the measured spectrum data on a point-by-point basis, the calibration factors for all measurement frequencies being interpolated from the look-up table calibration frequencies. Measured RF emission spectra are thus calibrated to power occurring at the noise diode calibration point.

As shown in Figure 7, the NTIA RF front end contains a built-in noise diode, but an external diode can be used if a different front-end system is used. This built-in diode will be used for the eNB measurement calibrations. For the UE spectrum measurements, however, a stand-alone noise diode will be used at the front of the first RF circulator, as shown in Figure 9.

9. Statistical Analysis

9.1. Relevant Experimental Variables

- **Response Variables**: Samples of power spectral density for OOBEs from AWS-3 LTE signals. Peak and RMS power will be measured at each frequency as described in Section 5. In addition, all power samples over the specified dwell time will be recorded at each frequency.
- **Controlled Variables**: measurement bandwidth, acquisition center frequency, attenuator setting, YIG tuning signal, LNA gain, measurement dwell time, LTE transmit settings (RB allocation and transmit power), experimental location (e.g., shielded room)
- **Uncontrolled Variables**: environmental temperature and humidity, spurious emissions from external sources, heating of UEs due to power dissipation

9.2. Potential Sources of Uncertainty

- Front-end gain
  - Determined from pre-test calibration with noise diode
  - Frequency dependent
  - Used to scale measured power
- Front-end noise
- RF connector repeatability (estimated from repeat measurements)
- RF radiated measurement repeatability (estimated from repeat measurements)
- Attenuator
  - Inaccurate steps
  - Frequency dependence
- Bandpass filter (YIG filter)
  - Non-flat passband
  - Error in YIG control signal
- Low Noise Amplifier (LNA)
  - Gain should be such that it drives system noise figure

- Impedance mismatches
- Accuracy of power measurement from spectrum analyzer
- LTE signal traffic
  - Resource Block allocations
  - Transmit power settings
  - Number and geometry of UEs
- Spurious environmental noise
- For radiated measurements:
  - Thermal noise from antenna
  - Channel variations

9.3. Analysis Plan

The emitted power $P(f)$, centered at frequency f, will be obtained by adding a gain factor $G(f)$ to the observed power $R(f)$ from the spectrum analyzer, i.e., $P(f) = G(f) + R(f)$, where $P(f)$ and $R(f)$ are expressed in dBm and $G(f)$ is expressed in dB. Alternatively, if $P(f)$ and $R(f)$ are expressed in Watts, we write $P(f) = G(f)R(f)$, where $G(f)$ is a dimensionless power ratio. To simplify our notation below, we suppress the frequency dependence.

Measurement uncertainty will be assessed by estimating a confidence interval for P at each frequency. Note that due to the frequency-stepped nature of the measurement method, it is safe to assume that measurements made at different frequencies will be statistically independent, and therefore, uncorrelated. We will assume that when P is expressed in Watts, it follows a normal distribution, and estimate a confidence interval from estimates of P and its variance, denoted $Var(P)$. The validity of the normality assumption will be checked with quantile-quantile (Q-Q) plots. In the event that this assumption is not met, resampling (e.g., bootstrapping) will be applied to estimate a confidence interval. Since the measured power will be reported in dBm, the confidence interval in Watts will be transformed to dBm. Due to the nonlinearity of this monotonic transformation, the resulting confidence interval in dBm will be asymmetric with respect to the estimate of P.

We can estimate both P and $Var(P)$ from repeated measurements of G and R. Specifically, suppose that we have $n_g$and n_r independent samples of G and R, respectively. Then the means and variances of G and R can be estimated from the sample with the usual unbiased sample means and variances, denoted $\bar{g}, \bar{r}, s_r^2$, and s_g^2. Since the gain will be estimated in pre-testing from independent measurements, it follows that G and R will be statistically independent. Under this assumption, $\hat{P} = \bar{g}\bar{r}$ is an unbiased estimated of P (in Watts), and a formula from [1] yields an unbiased estimate of $Var(\hat{P})$, given by

$$\widehat{Var}(\hat{P}) = \bar{g}^2 \frac{s_r^2}{n_r} + \bar{r}^2 \frac{s_g^2}{n_g} - \frac{s_g^2 s_r^2}{n_g n_r} \qquad (1)$$

The frequency-dependent gain factor, G, will be determined via a calibration using the Y-factor technique, which utilizes a noise diode as a standard noise source. By making repeated measurements of G at different attenuator settings, the gain variability in the entire front-end will be assessed. Remaining measurement uncertainty will be captured by making repeated measurements of R. It is desirable to acquire repeated measurements in pre-testing, so that the expected magnitude of uncertainties can be roughly estimated, and to aid planning of the final experiment.

In addition to the above uncertainty assessment, the measurement system will also be characterized with various secondary measurements in pre-testing, e.g.,

- System noise figure as function of frequency
- System frequency response
- Attenuator frequency response at various settings
- Assessment of impedance mismatches
- Assessment of change in UE emissions due to heating

If possible, uncertainties for these characterizations will be obtained from repeated measurements.

9.4. Potential Confounding Factors and Their Mitigation

Uncontrolled experimental factors include environmental conditions, spurious emissions from external sources, and heating of UEs due to power dissipation. The severity of these factors will be evaluated by visually inspecting scatter plots of all recorded power samples versus time.

Environmental conditions and spurious emissions can be controlled to a large degree for conducted measurements by carrying them out in a shielded room. For radiated measurements, environmental conditions and spurious emissions can be mitigated by using a longer dwell time and by distributing measurements over a longer time period. Changes in uplink LTE traffic due to UE power dissipation can be mitigated by shortening the UE transmission interval.

10. References

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[6] FCC Report and Order: "Amendment of the Commission's Rules with Regard to Commercial Operations in the 1695-1710 MHz, 1755-1780 MHz, and 2155-2180 MHz Bands", paragraph 62. March 31, 2014; retrieved from https://transition.fcc.gov/Daily_Releases/Daily_Business/2014/db0401/FCC-14-31A1.pdf

[7] 3GPP TR 36.101 "Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception;" retrieved from https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2411

[8] 3GPP 34.121 "Terminal conformance specification, Radio transmission and reception (FDD);" retrieved from https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2362

[9] 3GPP TR 36.141 "Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) conformance testing;" retrieved from https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2421

Appendix A - Phase I Measurements

To support the testing recommended in the Phase II Test Plan (main body of this document), Phase I measurements were conducted to shed light on the configurations required for both DUTs and measurement hardware. The purpose of the Phase II Test Plan is to define measurement methods for OOBE in AWS-3 bands (1755–1780 MHZ uplink and 2155–2180 downlink). Because AWS-3 (3GPP Band 66) is newly licensed, equipment was not available for testing. To determine the test methodologies (subject of Phase I), 3GPP Band 3 equipment was used. For Phase I, results are presented for a single UE and a single eNodeB.[9] Both the UE and eNodeB operate in 3GPP Band 3 also called LTE Band 3 (1710–1785 MHz uplink and 1805–1880 MHz downlink). Band 3 was chosen because the frequencies are close (the uplink overlaps) and the equipment is readily available. Band 3 is not used in North America but it is used in other parts of the world.

A.1. RF Preselector Characterization[10]

In Phase I, a characterization of the RF measurement system was performed. Specific to the RF preselector that was used, a vector network analyzer was used to characterize the attenuation and impedance of the system.

Specific to the front-end system used in Phase I (described in Section 3.1, and shown in Figure A-1), a series of measurements were done. The front end can be switched into several modes. In bypass, there is no filter and no LNA, so only the attenuator has an effect. The attenuation was measured in bypass mode, but at higher attenuations readings became noisy.

To account for that, measurements were attempted in some of the bandpass modes. These include 500 MHz to 1 GHz, 1 GHz to 2 GHz, and 2 GHz to 4 GHz. Each bandpass filter also had an LNA. These gave more useful numbers at high attenuation, but less so at low attenuation. Each of these measurements were used to characterize the attenuation of the system. These data were used in the statistical analysis.

A.2. UE Measurements

A.2.1. UE Measurement Setup

Figure A-1 shows a block diagram for the conducted UE measurement system. The custom RF front end was built by NTIA’s Institute for Telecommunication Sciences. The UE devices being measured use OFDM modulation and are frequency domain duplexed (FDD) with their controller. The controller was a Rohde & Schwartz Wideband Radio Communication Tester

[9] The validity of the test process is not dependent on the identity of the specific manufacturer of Band 3 equipment used.

[10] Note that this test plan uses the terms “RF Front End” and “Preselector” almost synonymously. The Preselector is a function and component of the RF Front End and consists, in the current case, of a tunable YIG Bandpass filter. See Phase II Test Plan Section 3.1 for details.

Model CMW-500 running as an evolved Node B (eNodeB). The CMW-500 parameters during the emission measurements are shown in Table A-1.

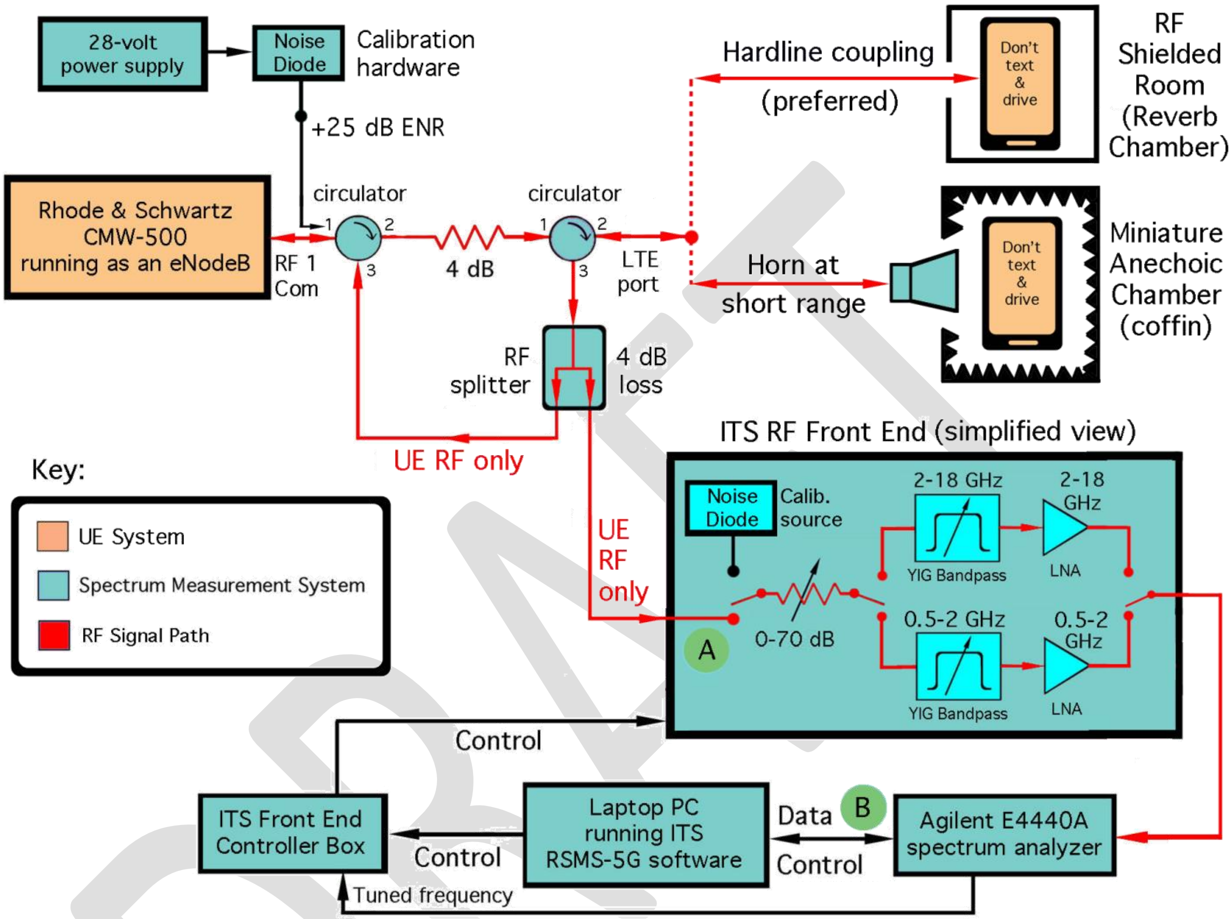

Figure A-1. Block diagram of the UE emission spectrum measurement system.

To isolate the UE signal from the CMW-500 eNodeB signal for the spectrum measurement, the measurement system used a pair of directional RF circulators,[11] as shown in Figure A-1. The circulators provide about 20 dB of decoupling. The CMW-500 was operated at the lowest possible power level that still allows control of the each UE being measured. These expedients (RF circulators and minimal CMW-500 power) kept the CMW-500 emissions from contaminating the UE emission spectrum measurement results.

The UE and eNodeB signals were thus forced to run in a loop[12] between the two LTE units, with the UE signal on one side of the loop and the eNodeB signal on the loop's other side. The measurement system takes the UE signal from an RF splitter on the UE side of the loop. The splitter has 4 dB of insertion loss; a 4 dB attenuator[13] was inserted between the circulators to

[11] Meca Electronics, Model # CN-1.400. The manufacturer's specification is "15 dB typical, 13 dB minimum." We measured the isolation to be greater than 18 dB across the frequency range of interest.
[12] The loop is formed by circulator 1, circulator 2, the left side of the RF splitter, and back to circulator 1.
[13] The 4dB attenuator was inserted to improve the impedance match between the two circulators.

ensure balanced RF path loss on both sides of the circulator loop. The measurement system noise figure from the input to the RF front end was approximately 8 dB. The gain of the measurement system was approximately 24 dB. The measurement system noise and gain are measured between the input of the ITS RF Front End (left side of the simplified view block: location “A” in Figure A-1) and the output of the Agilent spectrum analyzer (left side of the spectrum analyzer block: location “B” in Figure A-1).

Table A-1. Operating parameters of the R&S CMW-500 during UE spectrum measurements.

UE Parameter	**Parameter Value**
Duplexing	Frequency Division (FDD)
RF Modulation	Quadrature Phase Shift Keying (QPSK)
Operating Radio Band	3GPP Band 3 (1775 MHz)
UE Uplink Carrier Frequency	1775 MHz
Uplink Resource Block Allocation	50 RB
Commanded Full Cell Bandwidth	10.0 MHz (with 9 MHz actually occupied when 50 RBs were running)
Measured Total Output Power at Antenna Port	+20.5 dBm (measured with an external power meter across full LTE bandwidth of 9 MHz)
Resource Block (RB) Energy Per Resource Element (EPRE)	-100.0 dBm/15 kHz (indicated by eNodeB)
Full Cell Power	-72.2 dBm (indicated by eNodeB)
Physical Uplink Shared Channel (PUSCH) Open Loop	+23.0 dBm (indicated by eNodeB)
PUSCH Closed Loop	+30.0 dBm (indicated by eNodeB)
Switching	packet
State	Radio Resource Control (RRC)
Transfer Block Size Index (TBSI) (Downlink)	9
TBSI (Uplink)	6
Start Resource Block	0
Downlink Throughput (50 RBs)	4.795 Mbit/sec
Uplink Throughput (50 RBs)	2.064 Mbit/sec
Protocol	Internet Protocol Version 4
Antenna Gain	See main body text

In Phase I, the UE used had user accessible RF ports (located underneath the removable back cover of the UE). Therefore, a hardline connection was used for most measurements. However, in preparation for Phase II UEs that may not have accessible RF ports, a comparison measurement was done to demonstrate and verify that a radiated/coupled measurement would provide similar results. The radiated/coupled measurement was performed with a UE placed immediately in front of the aperture of a dual-ridged horn antenna inside a small anechoic chamber. Although the absolute power measurement at f_0 was different for the two measurements (as expected), the shape of the emission spectrum was the same for the two coupling methods (see Figure 5, main body of this document).

When coupled measurements were done in Phase I, the coupler was physically moved around the UE to determine the location where the energy coupled into the measurement system was maximized. Maximizing the coupled energy insures that the measurement system has sufficient dynamic range to make the measurement.

Figure A-2 shows the CMW-500 (top) used in this measurement. The spectrum analyzer shown (bottom) was only used for troubleshooting/verification.

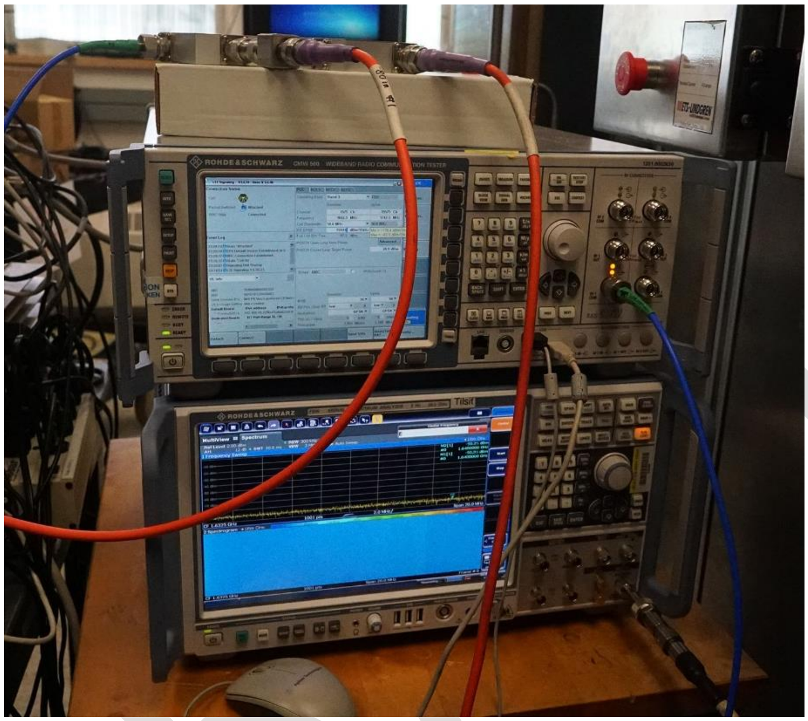

Figure A-2. The CMW-500 base station emulator (top) and one of the spectrum analyzers used to troubleshoot and verify the measurement setup (bottom).

The front-end/preselector and spectrum analyzer used to acquire the data in Phase I are shown in Figure A-3. The spectrum analyzer can be seen on the lower right side of the equipment stack (underneath the laptop). The three boxes on the left constitute the front-end/preselector.

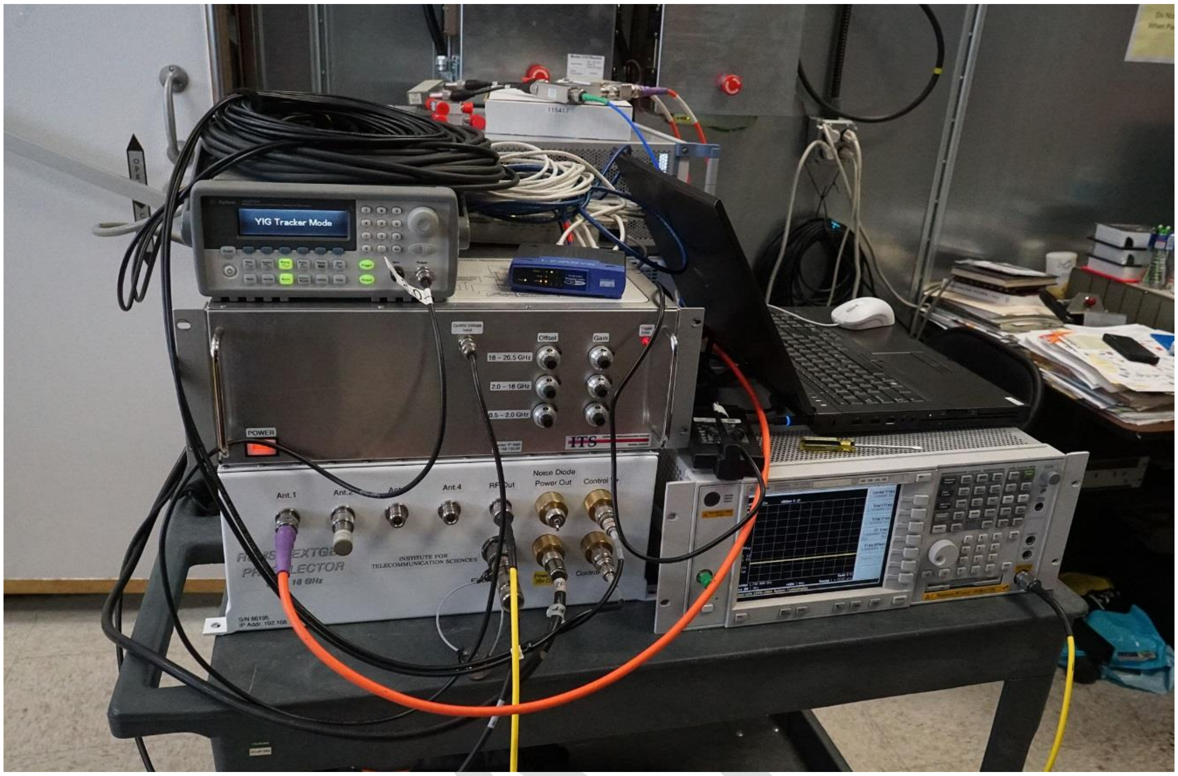

Figure A-3. The spectrum analyzer (bottom right), acquisition laptop (on top of the spectrum analyzer), and RF preselector (3 box stack) used for both the UE and eNodeB measurements.

Figure A-4 shows the hardline connection to the Phase I test UE. Figure A-5 shows the UE placed underneath the horn antenna for coupled/radiated testing.

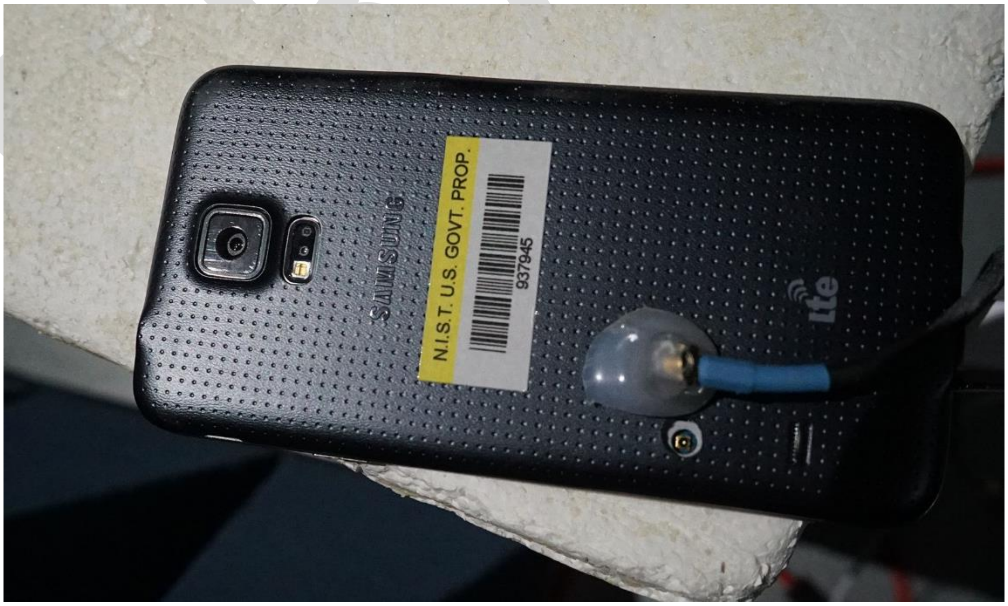

Figure A-4. The UE used in Phase I measurements, shown with the hardline attached to one of the RF ports.

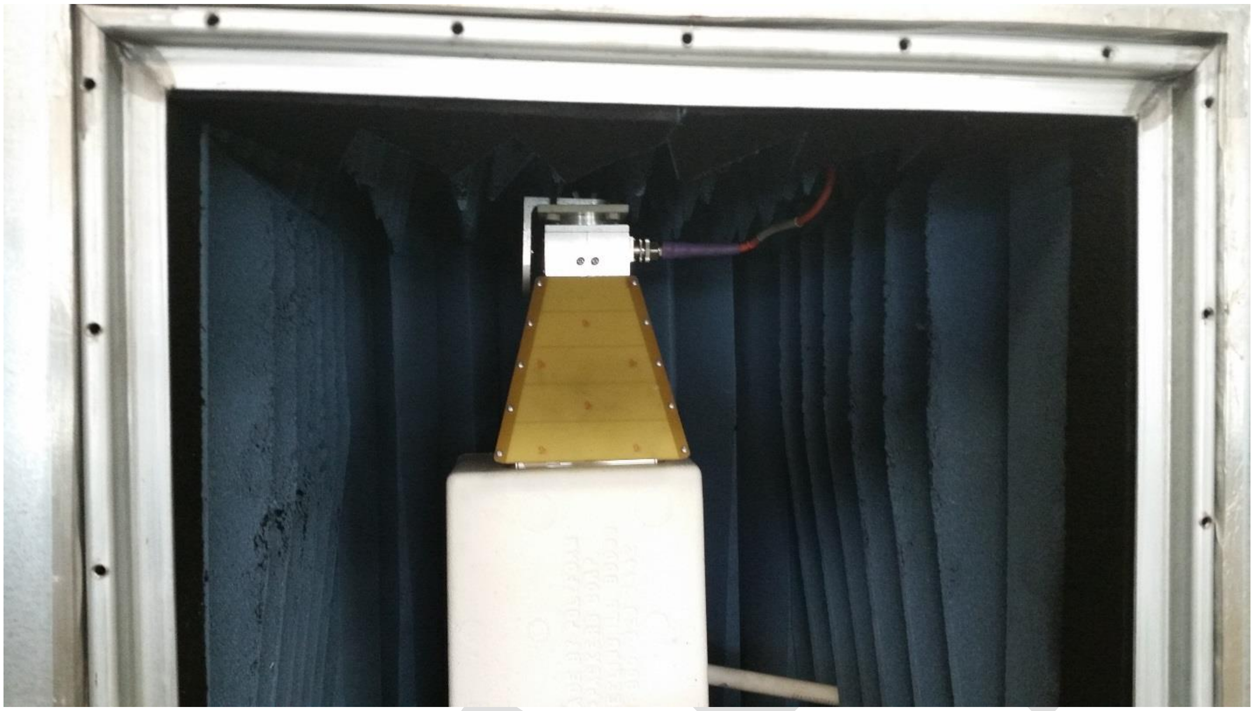

Figure A-5. The UE placed inside the small anechoic chamber during the coupled/radiated testing. The UE is placed on top of foam blocks, and appears as a silver line immediately underneath the horn antenna.

Prior to measuring the UE emissions as coupled into a horn antenna, an attempt was made to use a passive inductive coupler, as shown in Figure A-6. Two different couplers were attempted, but both suffered from the same issue: the placement of the coupler in relation to the phone was extremely sensitive. After trial-and-error testing, it was determined that for the coupler shown in Figure A-6, the location of maximum coupling was offset from the phone in both the vertical and translation axes. This sensitivity made the use of the couplers impractical.

Figure A-6. The Phase I test UE is shown with the passive coupler banded to it.

A.2.2. Phase I UE Measurement Procedure

As the goal of Phase I was to investigate configurations of equipment and DUTs, much of the process was done via trial-and-error. The results of these quick measurements led to the decisions reflected in the Phase II test plan (main body of this document). The following elements were explicitly investigated to determine whether or not they have an impact on the final emissions of a UE/eNodeB, or the measurement configuration:

- **Positive Peak vs. RMS Average Detectors on the Spectrum Analyzer**: Because LTE signals vary rapidly with time, we examined the impact of using a positive peak or RMS average detector. Ultimately this comes down to the preference of the end-user: both produce valid results. The peak detector would show the worst case scenario, but it would give no indication of how frequently it occurs. To be complete, we suggest obtaining measured data with both detector types because it will give a more complete picture of what is seen on average and “worst-case.” Both positive peak and RMS average detectors were examined in Phase I.
- **Resolution Bandwidth of the Spectrum Analyzer**: Varying the resolution bandwidth (RBW) of the spectrum analyzer impacts the “granularity” of the measured spectrum. Wide measurement bandwidths may obscure features in the spectrum that may be of interest. Narrow resolution bandwidth will provide more data, but take significantly more time to acquire. An additional consideration in the decision to use a given RBW is the end use of the data. If possible, the RBW of the measurement should match the RBW of the receiver of

interest (in this case an AMT receiver). Our understanding is that most AMT receivers use a RBW of 1 MHz, thus our suggestion is that most measurements be done with a 1 MHz RBW. This will help provide the most accurate picture of what the AMT receiver will “see.” Additional measurements are suggested in other RBWs for the purpose of future data analyses. In Phase I, RBWs of 100 KHz, 300 KHz, 1 MHz, and 3 MHz were examined.

- **LTE Resource Block Allocations**: The OOBE of an LTE device may vary based on the resource block allocation of a given frame. Because resource block allocations are made dynamically based on the number of users in a sector and their demand for data, we suggest measuring several resource block configurations. Previous work has shown that the susceptibility of some devices (other than AMT receivers) may be influenced by the spectral changes caused by resource block allocations. In Phase I, resource block allocations of 50 (full set), 25, 12, 5, and 1 were discussed. Only the full set of 50 was measured. The rest (25, 12, 5, and 1) will be considered for Phase II.
- **Modulation of Data within the LTE Signal**: The modulation of the data used within an LTE signal was examined. Two modulations were considered: QPSK and 16-QAM. The use of QPSK appeared to result in a slight increase in the OOBE at some frequencies. Increases did not exceed approximately 4 dB. Though 16-QAM may end up being more prevalent, we suggest conducting measurements using the QPSK modulation. Devices that are operating near the noise floor (e.g., edge of a cell) may use QPSK instead of 16-QAM.
- **Output Power of the CMW-500**: Ideally, the OOBE of the CMW-500 would have a negligible impact on the measurement of the UE’s OOBE. However, if the two are close enough in frequency, it may be possible for the CMW’s imperfections to influence the UE’s results. To limit this influence, we suggest keeping the output power of the CMW-500 at a minimum level. There is more risk of influence in the Phase I measurements because the UL and DL frequency bands are in much closer proximity than in actual AWS-3 deployments.

For all measurements performed on UEs, the UE power was maximized by turning down CMW-500 power until the UE lost communication, and then bringing CMW-500 power back up by 3 dB.

For Phase I, the emissions spectra measured were normalized to 0 dB at f_0 in 1 MHz resolution (IF) bandwidth.

Phase I data were collected by use of the stepped-frequency measurement technique. This technique provides a time-domain collection at each measurement step. Each measurement frequency step for all collected emission spectra consisted of 1001 data points in the time domain. All of these points were recorded.

A.2.3. Phase I UE Measurement Results

Figures A-7 and A-8 show the measured spectrum of the Band 3 UE. The FCC emissions mask is overlaid on the plots to illustrate the difference between the regulatory limit and the actual emissions.

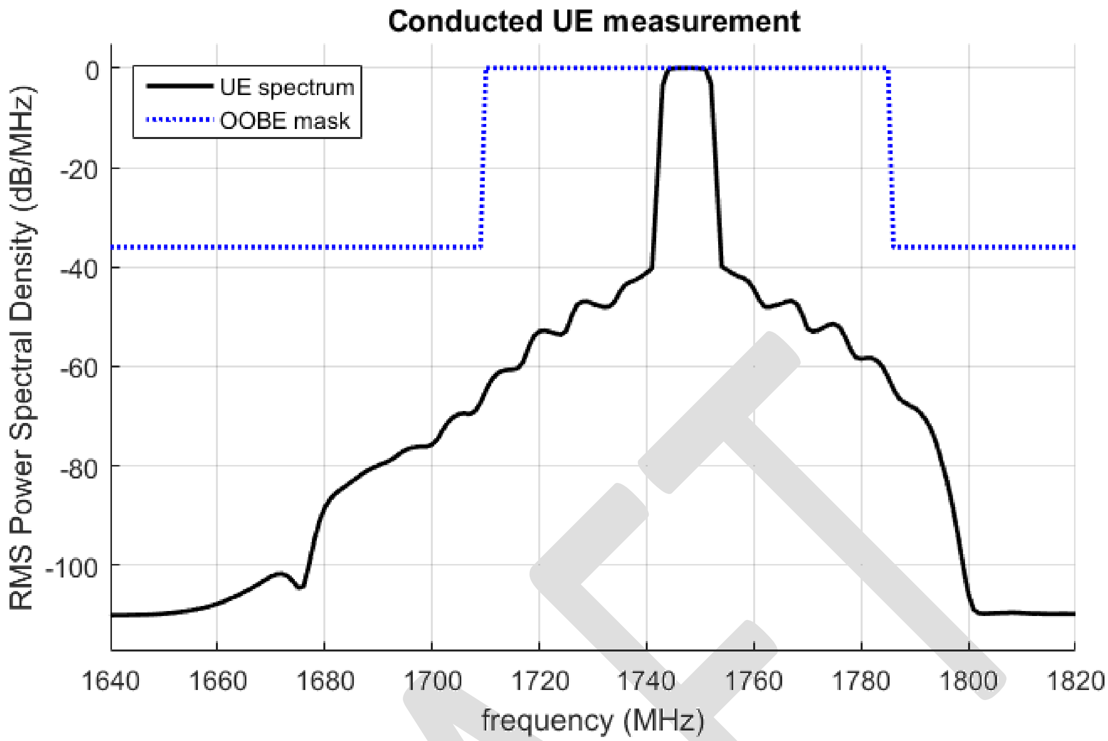

Figure A-7. Conducted UE emission spectrum measurement. UE was operated at maximum power with all resource blocks occupied.

From [A-1], we know that the emissions mask in AWS-3 is similar to limits seen in other bands. The required suppression, S, outside the band edges is S [dB] = {43 + 10log(P_{total})}. Suppression is given in dB below the maximum power, P_{total} in watts, that the transmitter is allowed to put into its own antenna. Transmitter antenna gain is not a factor in the mask limit. The suppression requirement is in units of decibels. The net effect is that the allowed OOBE is independent of transmitted power and is simply an absolute power level of -43 dBW or -13 dBm. Note that in Figures A-7 and A-8the +23 dBm UE transmit power appears at 0 dB due to normalization and the -13 dBm OOBE limit correspondingly appears at -36 dB.

The maximum width of the 95 % confidence intervals shown on these data was found to be 0.06 dB/MHz. However, this estimate includes the statistical factors analyzed (see Section 9), exclusive of the RF measurement repeatability. The confidence interval is so small that it would not show in Figure A-7.

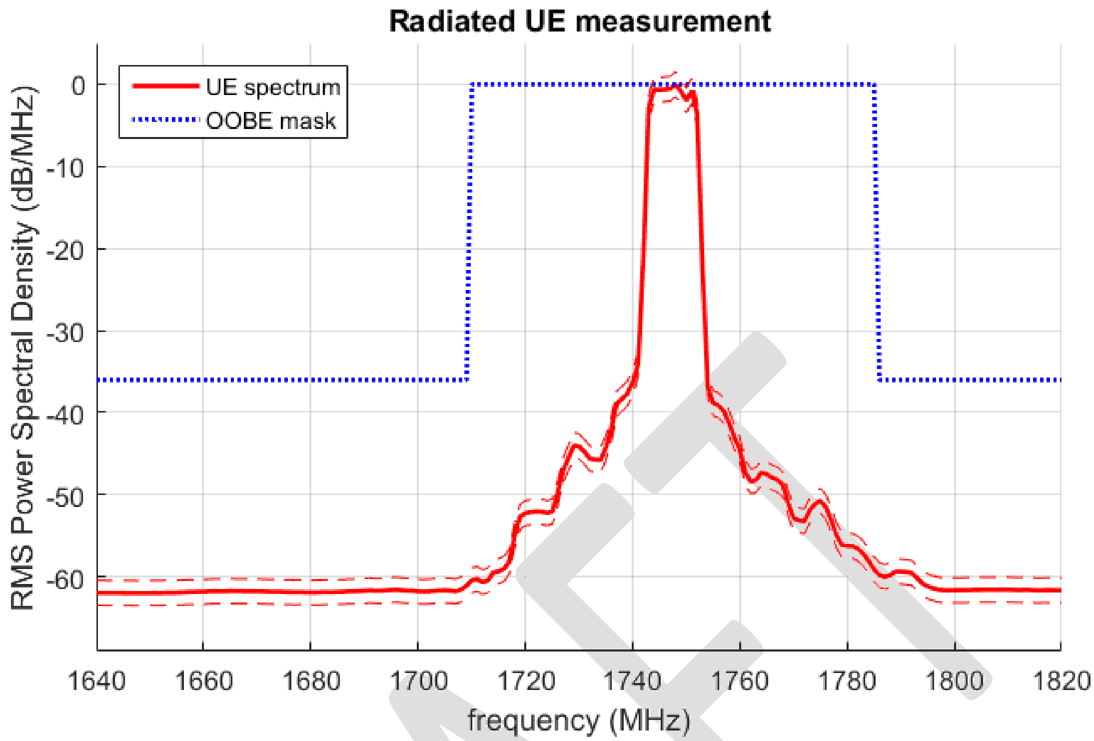

Figure A-8. Radiated UE emission spectrum measurement. UE was operated at maximum power with all resource blocks occupied. Dashed lines show this uncertainty.

A.2.4. Phase I UE Measurement Conclusions

The UE measurement data shown indicates that OOBE drop off significantly outside the band. Though these measurements were done on a Band 3 (uplink 1710-1785 MHz) UE, it is reasonable to expect that the shape of AWS-3 (uplink 1755-1780 MHz) UEs' OOBE, once deployed, should resemble this, as a similar type of power amplification and filtering will likely be used (but with different cut-off frequencies). Given that the measured UE spectra are more than 100 dB below the carrier frequency after +/−70 MHz, the +/−100 MHz suggested for Phase II should be more than adequate to capture the OOBE from AWS-3 hardware.

Again, the data shown here are only roughly indicative of what could be expected in AWS-3. The measurements shown above are only for a single UE from a single manufacturer in Band 3. However, given that 80% of the Band 3 UE UL band is contained within the AWS 3 UE UL band, the results may be very similar.

Once acquired, these data can be used as an input to a more complete coexistence analysis to examine the impacts of AWS-3 OOBE on AMT receivers.

A.3. eNodeB Measurements

Chronologically, the eNodeB measurements were performed after the UE measurements described in Section A.2 Therefore, there were few elements to investigate because the measurement system was already functioning and configured for LTE measurements. The fact that there is already a 3GPP defined eNodeB test mode for the measurement of emissions also limits the amount of additional work that needs to be done.

It is important to note that although we used 3GPP eNodeB test mode for these measurements, we did not use the 3GPP test method. Rather, we continued to use the high-dynamic range measurement method described in this document.

The LTE specifications found in 3GPP TS 36.141 [A-2] define the eNodeB standalone full-band transmission test mode. In this test mode, the eNodeB downlink emissions can be tested without the effect of UE uplink transmission. In Section 6.1.1 of the 3GPP document, several E-UTRA Test Models have been defined for setting up physical channels on the eNodeB to perform transmission testing. The most suitable model for measuring emissions from the transmission of an eNodeB is E-UTRA Test Mode (E-TM1.1). The characteristics of this model and its recommended usage are specified in Section 6.1.1.1 of 3GPP TS 36.141 [A-2].

A.3.1. eNodeB Measurement Setup

The measurement setup used to measure the eNodeB emissions was very similar to the setup used to measure the UE emissions. The output of the eNodeB was set to its maximum allowable output power, fed into an attenuator (to prevent burning out the measurement system), and then into the front-end/preselector. This setup is shown in Figure 10.Figure A-3.

Because the eNodeB's test mode forces the eNodeB to transmit with simulated downlink traffic, there is no need for a CMW-500, UE, or emulator of any kind.

The eNodeB used for Phase I measurements is a Nokia FXED, deployed in late 2014. It runs software version FL15A. The eNodeB hardware used in Phase I is shown in Figure A-9, and includes a power supply, CPU and remote radio head.

Figure A-9. The eNodeB hardware used in Phase I. The bottom of the three units is the power supply, the middle the CPU, and the top the remote radio head.

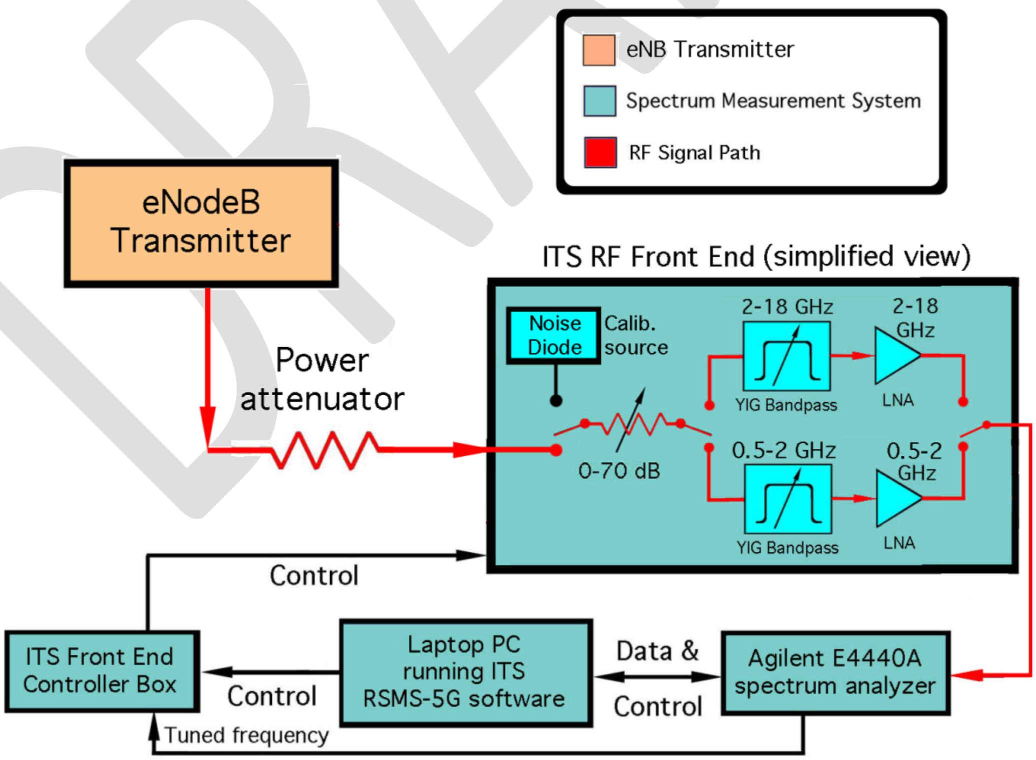

Figure A-10. eNodeB connection setup to measure downlink OOB emission.

A.3.2. eNodeB Measurement Procedure

The eNodeB measurement procedure was the same as the UE measurement procedure. The only difference was that the yttrium-iron-garnet (YIG) off-tuning technique was implemented. **Error! Reference source not found.** shows a graph of the YIG off-tuning technique used for the wide dynamic range measurements of the eNB. See Section 7 of the main body of this document (AWS-3 OOBE Measurements Test and Metrology Phase II Test Plan) for details.

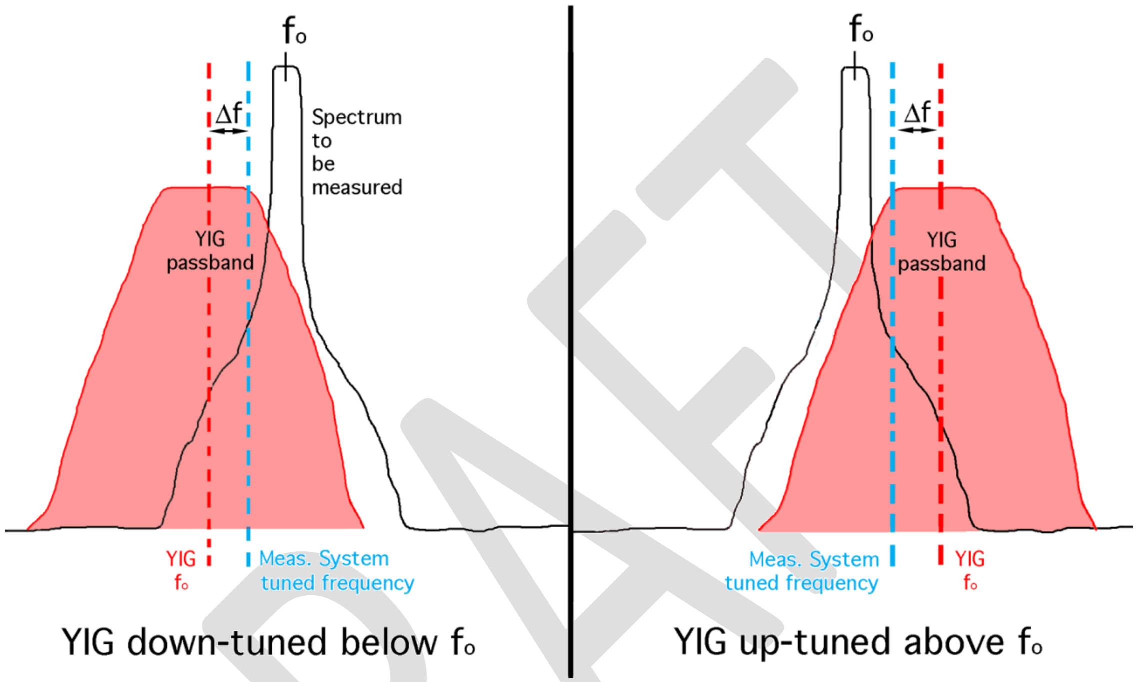

Figure A-11. YIG off-tuning technique used for wide dynamic range eNB emission spectrum measurements. The YIG center is offset (Δf) from the measurement system's tuned frequency up to the limit of the YIG's 3-dB roll-off points, half of the YIG's flat passband width.

A.3.3. Phase I eNodeB Measurement Results

Figure A-12 shows the emission spectrum measured from the eNodeB. As with the UE measurements, the FCC emissions mask is shown for illustration purposes. Note that the same compensation for the difference between total and measured emissions discussed in Section A.2.4 was applied here as well. Thus in Figure A-12 the +40 dBm eNodeB transmit power appears at 0 dB and the -13 dBm OOBE limit appears at -53 dB correspondingly. The maximum width of the 95 % confidence interval for the data shown is 0.10 dB/MHz. However, this confidence interval does not account for the RF connector repeatability.

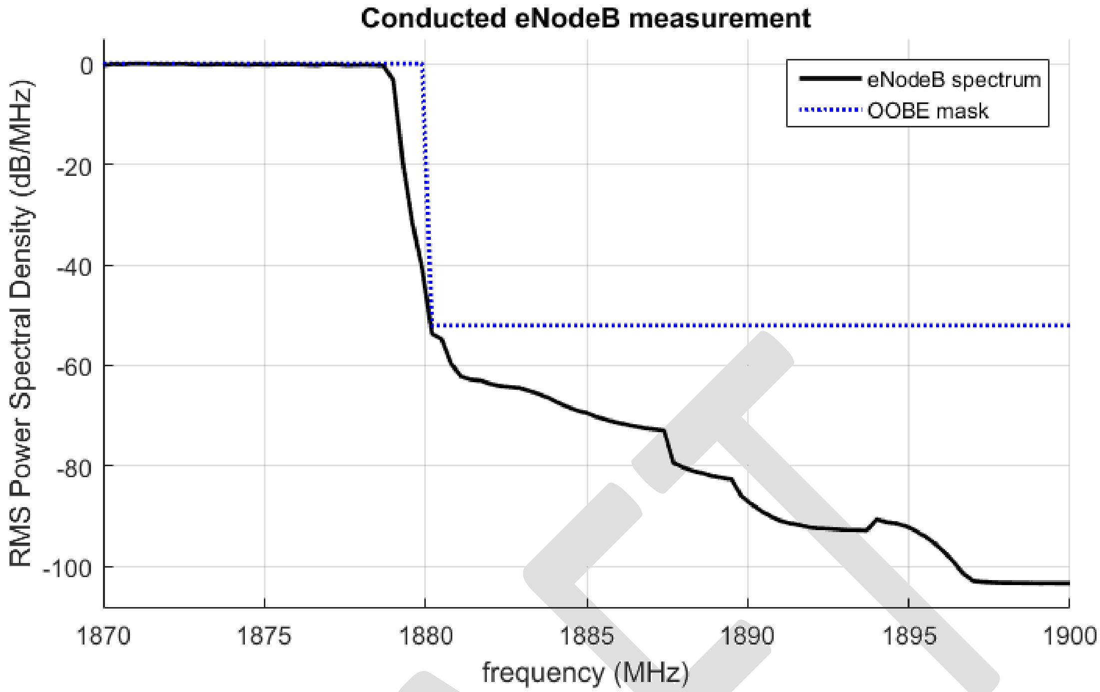

Figure A-12. eNodeB conducted emission spectrum measurement. Transmitter operated at maximum power.

A.3.4. Phase I eNodeB Measurement Conclusions

The eNodeB measurement data shown indicates that OOBE drop off significantly outside the band. Though these measurements were done on a Band 3 (downlink 1805-1880 MHz) eNodeB, it is reasonable to expect that the shape of AWS-3 (downlink 2155-2180 MHz) eNodeB OOBE, once deployed, should resemble this as a similar type of power amplification and filtering will likely be used (but with different cut-off frequencies). Given that the measured eNodeB spectra are more than 100 dB below the carrier frequency after +/−30 MHz, the +/−150 MHz suggested for Phase II should be more than adequate to capture the OOBE from AWS-3 hardware.

Again, the data shown here are only roughly indicative of what could be expected in AWS-3. The measurements shown above are only for a single eNodeB from a single manufacturer in Band 3.

Once acquired, these data can be used as an input to a more complete coexistence analysis to examine the impacts of AWS-3 OOBE on AMT receivers.

A.4. References

[A-1] FCC Report and Order: "Amendment of the Commission's Rules with Regard to Commercial Operations in the 1695-1710 MHz, 1755-1780 MHz, and 2155-2180 MHz Bands", paragraph 62. March 31, 2014; retrieved from https://transition.fcc.gov/Daily_Releases/Daily_Business/2014/db0401/FCC-14-31A1.pdf

[A-2] 3GPP TR 36.141 "Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) conformance testing;" ; retrieved from https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2421

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Arthur Webster, Sheryl Genco, Jason Coder, Brent Bedford, Adam Wunderlich, Jean-Aicard Fabien, Frank Sanders, John Ladbury, Azizollah Kord

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325 Broadway
Boulder, CO 80305

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14. ABSTRACT
Wide dynamic range emission measurements of LTE mobile phones (user equipment, or UEs) and base station hardware (eNodeBs) that will share spectrum with telemetry links in the newly available AWS-3 band U.S (designated Band 66 by 3GPP) are needed. These measurement results will be fed into interference analyses for band sharing studies. The ultimate goal is to know how much frequency and distance separation will be needed between LTE hardware and telemetry receivers, so as to preclude harmful interference from UEs to telemetry links when the band is eventually shared by these systems. This document describes emission measurements that will be performed on a variety of LTE UEs and eNodeBs that will be deployed in the AWS-3 band. As a precursor to these measurements, a measurement method is outlined and demonstrated for Band 3 hardware (note that the uplink for Bands 3 and 66 overlap).

15. SUBJECT TERMS
Band sharing; band sharing analysis; interference analysis; eNodeB (eNB); emission spectrum; telemetry links; user equipment (UE)

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