NTIA TR-26-582

U.S. Department of Commerce
National Telecommunications and Information Administration

Institute for Telecommunication Sciences Technical Report

Measured Out-of-Band Emissions in the 36–37 GHz Band from an n260 (37–40 GHz) Millimeter-Wave 5G Base Station

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June 2026
Boulder, Colorado
its.ntia.gov

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This publication is available free of charge from:
https://doi.org/10.70220/f69k22d6

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Abbreviations and Symbols

3GPP	3rd Generation Partnership Project
4G	fourth generation
5G	fifth generation
λ	wavelength
AC	alternating current
ADC	analog-to-digital converter
AGL	above ground level
CRAIN	ITS Communications Research and Innovation Network
CW	continuous wave
dB	decibel
dBi	decibel-isotropic
dBm	decibel-milliwatt
dBW	decibel-watt
DC	direct current
DoC	U.S. Department of Commerce
EIRP	effective isotropic radiated power in dBm
ENBW	equivalent noise bandwidth
EN-DC	Evolved-Universal Terrestrial Radio Access-New Radio Dual Connectivity
eNodeB	Evolved Node B
FCC	Federal Communications Commission
FDD	frequency division duplex
FNPRM	Further Notice of Proposed Rulemaking
ft	feet
GHz	gigahertz
gNodeB	Next Generation Node B

GNSS	Global Navigation Satellite System
G_r	receiver antenna gain in dBi
G_t	transmitter antenna gain in dBi
GUI	graphical user interface
HVAC	heating, ventilation, and air conditioning
IMT	International Mobile Telecommunications
ITS	Institute for Telecommunication Sciences
IP	internet protocol
IQ	in-phase and quadrature
ITU	International Telecommunication Union
km	kilometer
L_b	basic transmission loss in dB
L_{bfs}	free space path loss in dB
LNA	low-noise amplifier
LNP	low-noise path
LTE	Long Term Evolution
m	meter
Mbps	megabits per second
MHz	megahertz
MIMO	multiple input, multiple output
mmWave	millimeter wave
ms	millisecond
mW	milliwatt
NR	New Radio
ns	nanosecond
NSA	non-standalone
NTIA	National Telecommunications and Information Administration
OFDM	orthogonal frequency-division multiplexing

OOBE	out-of-band emissions
OSM	Office of Spectrum Management
PAPR	peak-to-average power ratio in dB
PN	pseudorandom noise
P_r	received signal power in dBm
P_t	transmitter power in dBm
RF	radio frequency
RSRP	Reference Signal Receive Power
RSRQ	Reference Signal Receive Quality
SA	standalone
SINR	signal-to-interference-plus-noise ratio
SPDT	single-pole double-throw
SSB	synchronization signal block
TCP	transmission control protocol
TDD	time division duplex
TRP	total radiated power
UDP	user datagram protocol
UE	user equipment
WRC-19	ITU World Radiocommunication Conference 2019
YIG	yttrium-iron-garnet

Measured Out-of-Band Emissions in the 36–37 GHz Band from an n260 (37–40 GHz) Millimeter-Wave 5G Base Station

Jeffery A. Wepman,[1] Silas T. Thompson,[1] Ryan S. McCullough,[1] Edward F. Drocella,[2] April Lundy,[3] Gerardo C. Saqueton,[1] and Kenneth J. Brewster[1]

Abstract: Out-of-band emissions (OOBE) measurements in the 36–37 GHz band were performed on a commercially available outdoor 5G millimeter-wave (mmWave) gNodeB operating in the n260 band (37–40 GHz). The 5G mmWave gNodeB is part of the Institute for Telecommunication Sciences (ITS) 5G mmWave test cell site located at the U.S. Department of Commerce Table Mountain Field Site and Radio Quiet Zone near Boulder, Colorado. The test cell site and measurement system used to perform these field measurements are described. Several spectrum captures are included to display both the in-band and out-of-band frequency characteristics of the mmWave signals. Determination of effective isotropic radiated power and a method to approximate the inferred total radiated power are included. These are used to facilitate the comparison of ITS OOBE measurement results to the limits set by the International Telecommunication Union Resolution 243 World Radiocommunication Conference 2019 specifications.

Keywords: 36–37 GHz, 37–40 GHz, 5G, emissions measurements, gNodeB, International Telecommunication Union Resolution 243, millimeter wave, n260 band, out-of-band emissions, OOBE, total radiated power, TRP

1. Introduction

The Federal Communications Commission (FCC) WT[4] Docket No. 24-243 Report and Order and Sixth Report and Order [1] establishes a framework for Federal and non-Federal user spectrum sharing in the 37–37.6 GHz band (Lower 37 GHz band). The Further Notice of Proposed Rulemaking (FNPRM) in this docket requests comments on revising the emissions limits for Upper Microwave Flexible Use Service operations above 37 GHz to protect passive

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[4] WT refers to the FCC Wireless Telecommunications Bureau.

sensors in the adjacent 36–37 GHz band. As one possibility, the FCC is considering adopting the emissions limits specified in International Telecommunication Union (ITU) Resolution 243 World Radiocommunication Conference 2019 (WRC-19) [2], hereafter referred to as ITU Resolution 243.

The objective of the work described in this report is to provide measured out-of-band emissions (OOBE) data on a commercially available cellular system operating in the 37–37.6 GHz band. The data are intended to be used to assist in providing input for the FNPRM.

To meet this objective, the Institute for Telecommunication Sciences (ITS), as requested by the Office of Spectrum Management (OSM) of the U.S. Department of Commerce's National Telecommunications and Information Administration, performed a set of OOBE measurements in the 36–37 GHz band. Additional OOBE measurements were also conducted to observe the behavior of the OOBE below 36 GHz.

The measurements were performed during the summer of 2025 on a Tier 1 commercial outdoor 5G millimeter-wave (mmWave) gNodeB[5] operating in the n260 Band (37–40 GHz) located at the U.S. Department of Commerce (DoC) Table Mountain Field Site and Radio Quiet Zone near Boulder, Colorado (hereafter referred to as Table Mountain) [3]. Location coordinates of the mmWave gNodeB radio tower on Table Mountain are given in Section 6.1. The commercially available Tier 1 mmWave gNodeB is part of the ITS 5G mmWave test cell site at Table Mountain. The ITS 5G mmWave test cell site is described in more detail in Section 2. For these OOBE measurements, the mmWave gNodeB was set up to operate with maximum power output (specified by the manufacturer to be nominally +29 dBm into each of two antenna arrays)[6] on a single 100 MHz carrier. The measurements were performed with a center frequency of 37.05 GHz and then repeated with a center frequency of 37.2 GHz.

[5] A 5G cellular system base station is commonly referred to as a gNodeB. The 5G mmWave gNodeB will be referred to as the mmWave gNodeB in the remainder of this report.
[6] The mmWave gNodeB radio includes a radio transceiver and two integrated antenna arrays. One antenna array generates vertically polarized transmissions while the other generates horizontally polarized transmissions.

2. ITS 5G Millimeter-Wave Test Cell Site

To facilitate the OOBE measurements, ITS established a test 5G mmWave cell site at Table Mountain [3]. The establishment of this test cell site was made possible by an expansion of the ITS Communications Research and Innovation Network (CRAIN) Laboratory 5G testbed previously deployed at the DoC Boulder Laboratories located at 325 Broadway in Boulder, Colorado [4].

The CRAIN Laboratory 5G testbed is a Tier 1 commercial grade 5G system that consists of a non-standalone (NSA) core, a standalone (SA) core, a fourth-generation (4G) Long Term Evolution (LTE) eNodeB,[7] and sub-6 GHz gNodeBs. NSA operation requires an eNodeB that serves as an anchor radio along with a gNodeB. SA operation eliminates the need for the anchor radio; the gNodeB connects directly to the 5G core.

The test cell site consists of a mmWave gNodeB along with its associated eNodeB. This includes an eNodeB baseband unit that connects to the NSA core, a mmWave gNodeB baseband unit, an eNodeB radio that operates in Band 66 (1710–1780 MHz uplink, 2110–2200 MHz downlink) that serves as the anchor radio, an LTE panel antenna, and a mmWave gNodeB radio that operates in Band n260 (37–40 GHz). Note that Band 66 is a frequency division duplex (FDD) band, whereas Band n260 is a time division duplex (TDD) band. Although the mmWave gNodeB initially supported only NSA operation, and the test cell site at Table Mountain currently operates in NSA mode, SA operation is now available and is planned to be implemented in the future.

A tremendous benefit of the test 5G mmWave cell site is that measurements can be conducted in a highly controlled environment on a simplified but real commercial operational cell site. Having full control of the cell site, including the mmWave gNodeB, the UEs, and the propagation environment, provides an exceptional opportunity to evaluate OOBE from the mmWave gNodeB under very well-known and repeatable operating conditions. Measurements of OOBE under very well-known and repeatable operating conditions cannot easily be made on a mmWave gNodeB operating in a typical actively operational for-profit commercial cell site.

Furthermore, it is not uncommon for mmWave devices, such as mmWave gNodeB radios, to have integrated antennas – i.e., the radio transmitter and its antennas, as well as the radio receiver and its antennas, are not separable. For these mmWave devices, performing conducted measurements is not possible because there are no RF ports accessible for testing. RF measurements on these mmWave devices can only be radiated measurements, precluding typical measurements in an ordinary laboratory environment.

[7] A 4G cellular system base station is commonly referred to as an eNodeB. The 4G LTE eNodeB will be referred to as the eNodeB in the remainder of this report.

2.1 Test Cell Site Architecture

Wireless NSA systems support Evolved-Universal Terrestrial Radio Access-New Radio (NR)[8] Dual Connectivity (EN-DC). With EN-DC, a user equipment (UE)[9] initially attaches to an eNodeB and then also connects to a gNodeB. This dual connectivity allows the UE to increase the bandwidth it receives, which increases downlink throughput. This dual connectivity feature is described in 3rd Generation Partnership Project (3GPP) Release 15 [5]. For the specific test cell site deployed at Table Mountain, the eNodeB transmits a 5 MHz signal and the mmWave gNodeB transmits a 100 MHz signal (when operating in the single-carrier mode).[10] In this EN-DC mode, the connection between the UE and the network is established and maintained by the eNodeB and 4G NSA core. However, the UE receives data traffic from both the eNodeB and the mmWave gNodeB. EN-DC allows gNodeB deployments and operation to leverage existing 4G cores without having to deploy an additional 5G core.

The interface between the NSA core located at the DoC Boulder Laboratories and the eNodeB/mmWave gNodeB combination at Table Mountain requires a 10 Gbps Ethernet connection. This Ethernet connection allows the links to be established between the eNodeB and mmWave gNodeB and the NSA core.

The eNodeB radio operating in Band 66 was configured via its graphical user interface (GUI) to transmit at its minimum transmit power of +37 dBm (5 Watts) per RF channel.[11] Significantly less power was required to support EN-DC. Since the eNodeB radio is configured to transmit in 2 × 2 multiple input, multiple output (MIMO) mode, there are two transmit paths from the eNodeB radio to its antenna. On each transmit path, a series combination of fixed and variable step attenuators and a directional coupler are placed in-line between the transmitter output and the cable to the antenna. This configuration provides a maximum of up to +5 dBm transmit power at the antenna ports. The power level delivered to the antenna ports was measured using the directional coupler and a Keysight FieldFox N9952B handheld microwave analyzer operating in the Spectrum Analyzer Mode. During actual testing, it was found that power levels lower than +5 dBm were sufficient to support EN-DC operations with the mmWave gNodeB. Power levels of about −6.5 dBm to each antenna port were used and verified by measurements. These levels proved to be entirely sufficient for operation and minimized potential interference with the existing Band 66 spectrum owner.

The mmWave gNodeB radio, operating in Band n260, was configured to transmit in 2 × 2 MIMO mode. The mmWave gNodeB radio can transmit with a power level of up to +29 dBm per transmit channel, for a total of +32 dBm. Since the antenna has a nominal gain of 23 dBi, a total average effective isotropic radiated power (EIRP) of +55 dBm was achieved. The mmWave gNodeB radio can be configured to transmit several different antenna beamsets. A

[8] The term NR is essentially synonymous with the term 5G.
[9] A UE is a more formal term for a cellphone or cellular handset.
[10] Single-carrier mode was used for all the measurements performed in this study. While not used in this study, the test cell site is capable of multi-carrier mode operation where up to four 100 MHz carriers can be aggregated.
[11] The goal was to minimize the eNodeB radio power to reduce potential interference into LTE Band 66. This does not affect the goal of this study, emissions measurements on the mmWave gNodeB radio, at all since the eNodeB radio is completely separate from the mmWave gNodeB radio.

beamset defines the antenna patterns for the individual antenna beams that the mmWave gNodeB can produce.

2.2 Test Cell Site Location

The test cell site was deployed at Building T2 at Table Mountain. Figure 1 shows an aerial view of Table Mountain and Figure 2 shows a map with the location of Building T2 and nearby existing roads. This location was selected for several reasons.

First, Table Mountain provides an ideal environment for conducting over-the-air measurements in a very controlled outdoor environment. Table Mountain is an elevated, approximately 1700-acre, generally flat-top butte consisting of open prairie with scarcely any trees. There are just a few very sparsely spaced single-story buildings and other structures, such as antenna towers, located on the mesa.

Second, Building T2 is particularly well-suited for conducting radiated RF measurements on a cellular base station as it is located somewhat near the center of the mesa and has proximity to several existing roads that can be used for measurement system drive testing.

Third, Building T2 had many existing required and desirable facilities for deployment of a 5G cell site, such as AC power, an HVAC system, network connectivity, an easily accessible roof platform, and several openings in the walls and ceiling providing cable routing from within the building to outside the building.

Figure 1. Aerial view of Table Mountain. Credit: ITS Staff.

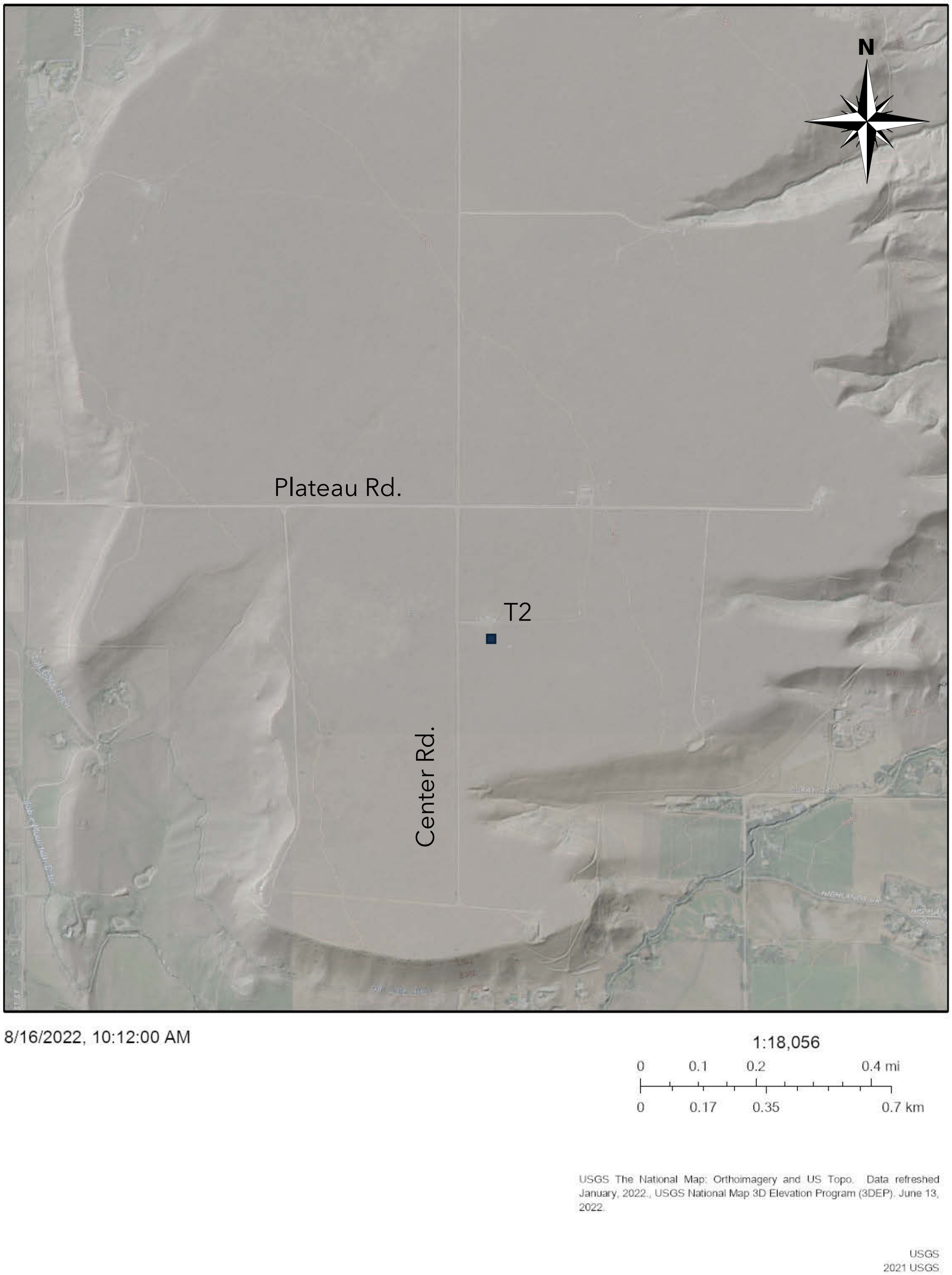

Figure 2. Test cell site at Building T2 on Table Mountain. Credit: USGS The National Map: Orthoimagery and US Topo. Data refreshed January 2022. USGS National Map 3D Elevation Program (3DEP), June 13, 2022.

2.3 Test Cell Site Equipment

No tower existed at Building T2, so a mobile antenna tower was used to mount the 4G LTE antenna and the mmWave gNodeB radio at suitable heights to perform the OOBE testing. The 4G LTE antenna is mounted at a radiation center of 5 m above ground level (AGL). The mmWave gNodeB radio is mounted on an azimuthal rotator (Hy-Gain Ham IV) attached to the tower below the LTE antenna at a radiation center of about 3.8 m AGL, as seen in Figure 3.[12] The rotator is connected to a digital rotator controller (Hy-Gain DCU-1) located in Building T2 via a conducted control cable. The rotator provides only relative azimuthal position, not absolute azimuthal position.[13] Because of this, a precision pointing device, the Sunsight Instruments MW08, was used to determine the pointing angle of the mmWave gNodeB radio as the rotator was moved. The azimuthal accuracy of the MW08 is stated by the manufacturer to be 0.08° [6].

[12] The LTE antenna was mounted at 5 m AGL to minimize potential interference with DISH Wireless UEs along U.S. Highway 36 west of the test cell site location because the LTE radio transmitted on the same 5 MHz channel owned and operated by DISH Wireless. The height of 3.8 m AGL for the mmWave gNodeB was chosen to minimize the amount of downtilt required to maximize the received power at the measurement receiver antenna, which was mounted on top of the measurement vehicle. Another constraint was that the tower had limited locations where the mmWave gNodeB could be mounted.

[13] This was the only antenna positioner that was available at ITS at the time for these measurements. A new antenna positioner with pan and tilt and absolute azimuthal position capability has since been installed for position control of the mmWave gNodeB.

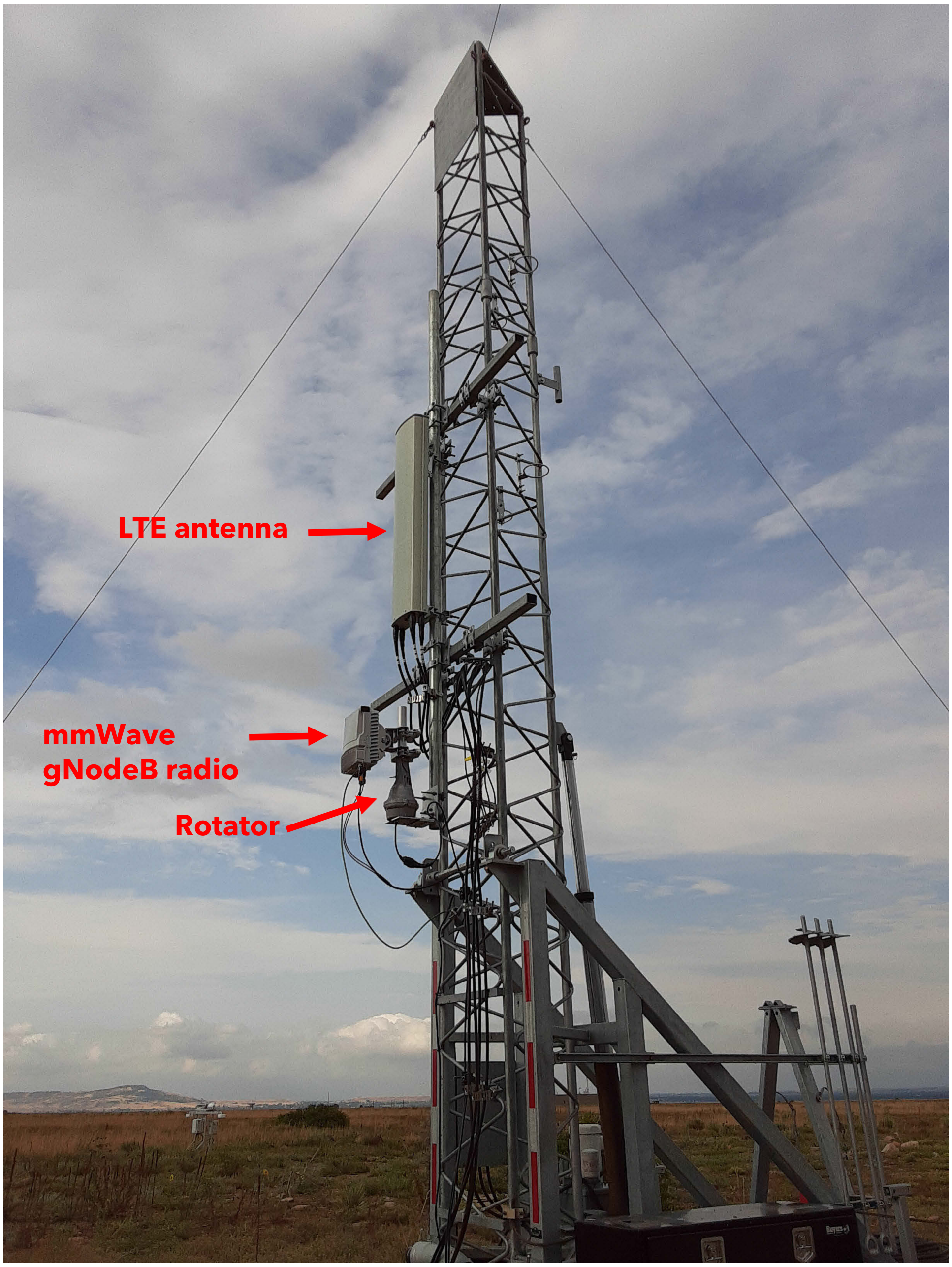

Figure 3. Mobile antenna tower with LTE antenna, mmWave gNodeB radio, and rotator. Credit: ITS Staff.

All the radio equipment, which includes the radios and the baseband units, requires −48 Volt DC power. No −48 Volt DC system existed at Building T2, so one was acquired and installed.

The baseband units for both the eNodeB and the mmWave gNodeB are located in an equipment rack inside Building T2. This equipment rack also includes a DC power distribution unit and the LTE Band 66 eNodeB radio.

3. ITS Millimeter-Wave Out-of-Band Emissions Measurement System

The measurements were made using a new mmWave OOBE Measurement System custom-built by ITS. A block diagram of the measurement system is shown in Figure 4. The measurement system consists of an RF antenna, preselector, signal analyzer, Global Navigation Satellite System (GNSS) disciplined frequency reference (with associated antenna), GNSS receiver (with associated antennas), measurement controller, and measurement laptop computer. For these measurements, the measurement system was installed in the ITS modified Chevrolet Express 3500 Passenger Van shown in Figure 5.

The measurement system RF antenna used was a Penn Engineering Components Ka band (26.5–40 GHz) standard gain horn with a nominal gain of 15 dBi and approximately 32° 3dB azimuthal and elevation beamwidth. The gain at 37 GHz was measured to be 16.5 dBi by using the three-antenna method for determining antenna gain as described in Section 5.1. For these measurements, the horn antenna was oriented to receive vertically polarized transmissions.

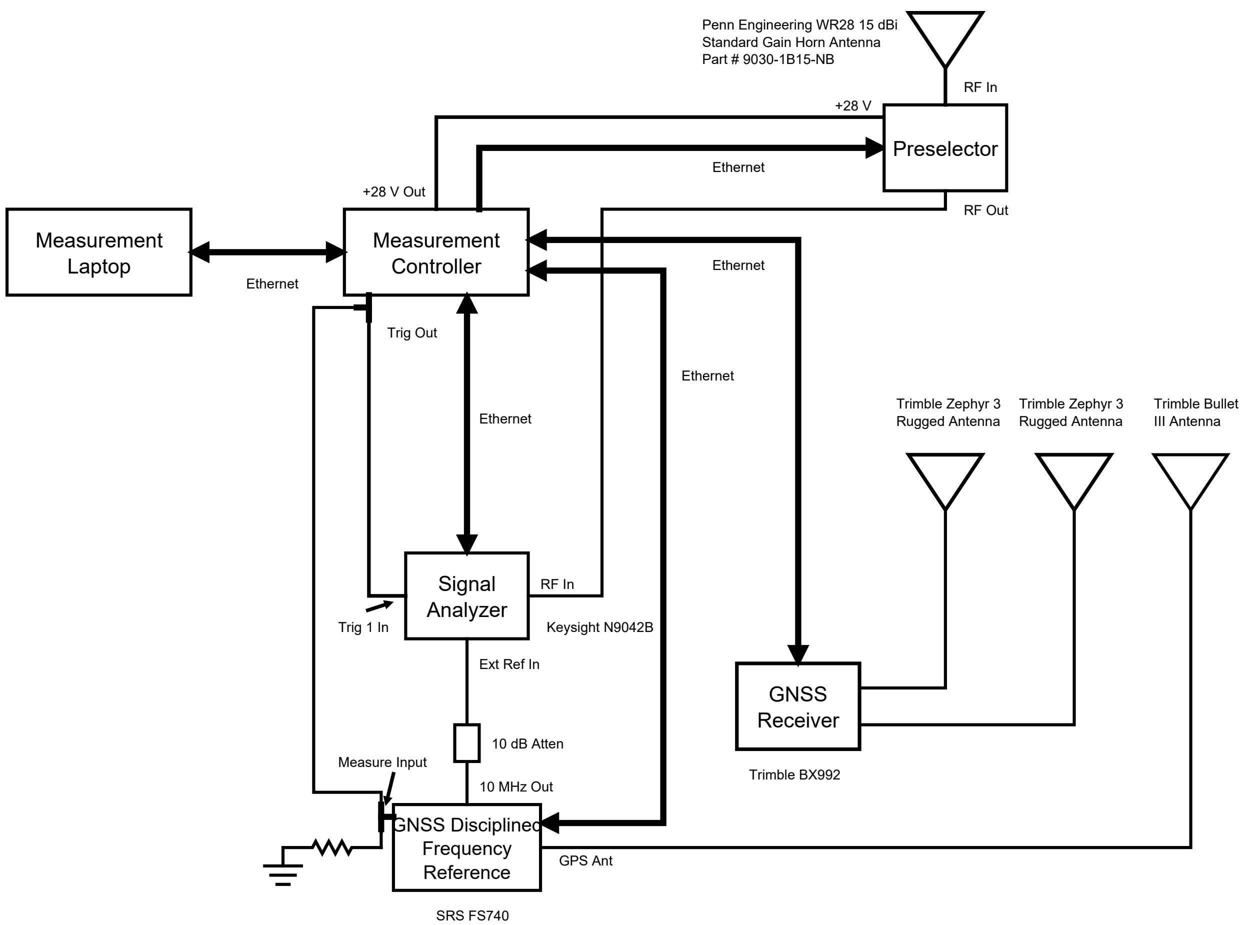

Figure 4. Block diagram of the ITS mmWave OOBE measurement system.

Figure 5. Measurement system vehicle: ITS modified Chevrolet Express 3500 passenger van. Credit: ITS Staff

The preselector performs several crucial functions for the measurement system. It attenuates unwanted out-of-band signals, improves the sensitivity of the system, facilitates adjustment of the dynamic range of the system, and enables noise diode measurement system calibrations. Noise diode measurement system calibrations provide measurements of the preselector gain and system noise figure (NF). By knowing expected preselector gain and NF values, noise diode measurement system calibrations can also be used to ensure that the measurement system is operating properly. The system noise level in a given bandwidth can be determined from the system NF. Preselector gain is particularly important to be able to determine absolute received power at the antenna output. A block diagram of the OOBE preselector custom-built by ITS is shown in Figure 6.

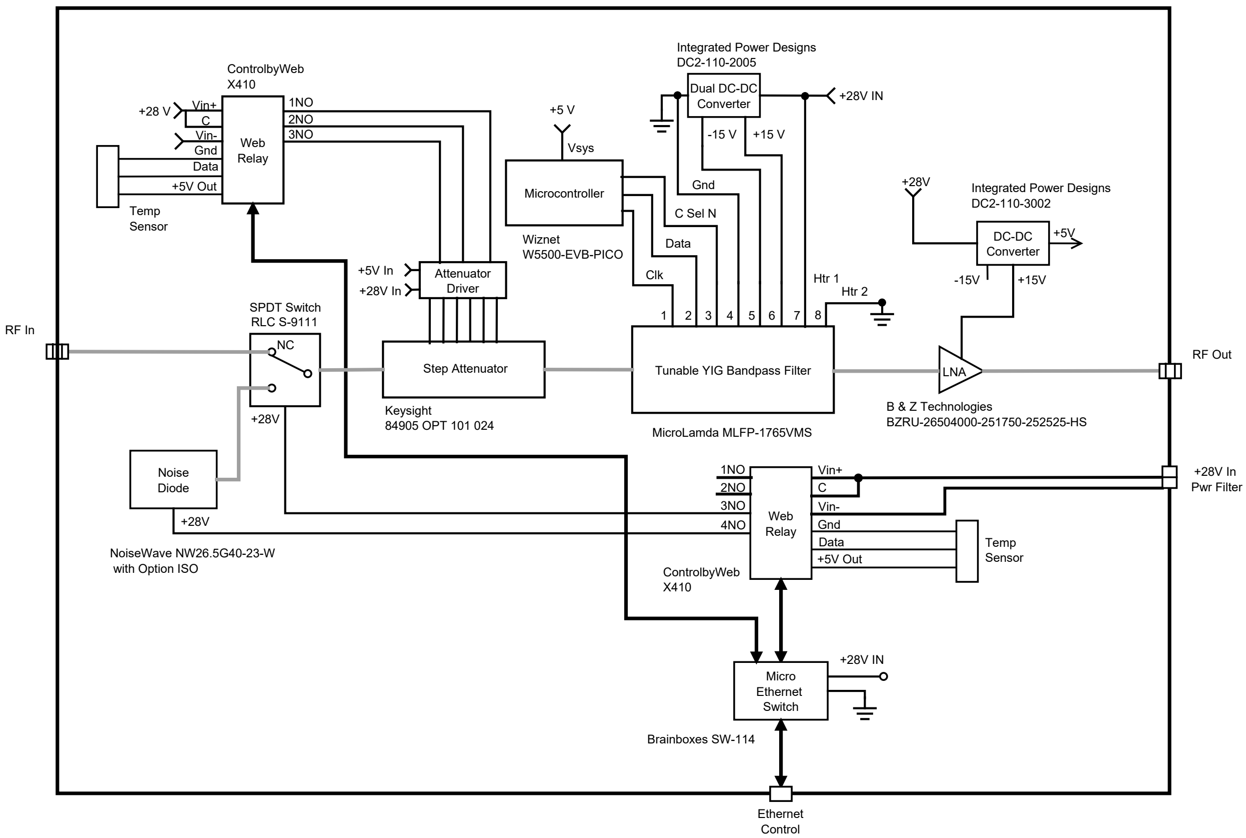

Figure 6. Block diagram of the ITS custom-built OOBE mmWave preselector.

The preselector provides a single RF path with a selectable RF input using a waveguide single-pole double-throw (SPDT) switch. Under software control, the user may select either the antenna input port or a built-in noise diode. During a measurement, the antenna input port is selected. The noise diode input is selected when a measurement system noise diode calibration is desired. After the RF input switch, the RF path consists of an electronically controlled step attenuator, tunable yttrium-iron-garnet (YIG) bandpass filter, and low-noise amplifier (LNA). The step attenuator provides attenuation of high-power signals. The tunable YIG bandpass filter ensures that signals outside of the desired measurement bandwidth are sufficiently attenuated. The LNA allows the best practicable measurement system sensitivity to be achieved.

Selection of waveguide or coaxial components was based on optimizing RF performance and the availability of commercial components. Where feasible, waveguide components were selected since they reduce insertion loss and provide higher system sensitivity. Therefore, the noise diode and SPDT switch were implemented as WR-28 waveguide components and the YIG bandpass filter and LNA were implemented as coaxial components.

The signal analyzer forms the core of the overall measurement system. For the OOBE measurements, a Keysight N9042B UXA mmWave signal analyzer was used in the traditional Spectrum Analyzer Mode. The signal analyzer provides measurements, in a user-selected bandwidth, of the RF transmissions received by the antenna and conditioned by the preselector. For the measurements conducted in this report, a 1 MHz resolution bandwidth was used. This bandwidth was chosen because it is a common, standard bandwidth used in spectrum measurements by regulatory agencies such as the FCC and therefore provides for simpler comparison to other potentially available measured data. Additionally, since narrower resolution bandwidths require more frequency steps in a stepped-spectrum measurement, as is used in the measurements conducted in this report, the 1 MHz resolution bandwidth is a good choice, since it is reasonably narrow and yet keeps the number of frequency steps manageable.

Automated control of the preselector and signal analyzer is provided by the laptop computer running measurement system control software developed by ITS. The measurement system control software implements a stepped-spectrum measurement method, described in Section 4, to perform the OOBE measurements. The software is implemented in Python and runs on a Linux operating system. The measurement controller consists of an Ethernet switch, a power supply for the preselector, and an Ethernet-controlled trigger pulse generator.

The pulse generator is used to initiate data collection by the signal analyzer by generating an external trigger pulse to the Trigger 1 Input of the signal analyzer. While the generation of the trigger pulse is asynchronous, the exact UTC time (to better than 100 ns accuracy) of the rising edge of the trigger pulse is captured using the Measurement Input of the Stanford Research Systems (SRS) FS740 GNSS-disciplined frequency reference. The rising edge of the trigger pulse initiates data collection on the signal analyzer, so the exact time RF data collection occurs is also known. The GNSS-disciplined frequency reference also provides a 10 MHz reference signal to the frequency reference input of the signal analyzer. The GNSS-disciplined frequency reference is set to automatically tune its reference frequency to received GNSS signals. The SRS FS740 updates its reference signal frequency every second.[14]

The signal analyzer collects the received signal power measured data; the data are then saved to a local hard drive on the laptop computer. The system is designed so that position data from the GNSS receiver and received signal RF data are collected simultaneously. The OOBE measurements in this study were taken at a fixed location. However, the capability of collecting position data along with the received signal RF data was implemented to support future mobile measurements.[15] Nevertheless, the position data and the received signal power measured data were saved to the hard disk on the personal computer.

[14] It is not uncommon that the reference signal frequency is updated less frequently in GNSS-disciplined frequency references.

[15] Simultaneously collecting both position and received signal RF data is necessary whenever using the system to perform mobile measurements. This provides the capability to correlate position with the received signal RF data.

4. Stepped Spectrum Measurement Method

This section provides a general, high-level description of the stepped spectrum measurement method. This method was used for the OOBE measurements performed for this study. The specific parameters used are provided in Section 7.

For the stepped spectrum measurement, a sequence of zero-span (time domain amplitude), relatively narrow resolution bandwidth data captures is performed over the entire frequency range of interest using the signal analyzer in the Spectrum Analyzer Mode. The signal analyzer is initially tuned to a fixed frequency at a desired starting frequency, and a time domain amplitude data capture is made. The signal analyzer is then further tuned (stepped) to the next desired fixed frequency, and another time domain amplitude data capture is made. This process is continued until measurement at the desired stopping frequency is completed. A single power value (typically peak or average value) is determined from each time domain amplitude data capture, and this result is plotted for each fixed frequency in the stepped spectrum measurement. This results in a plot of the received signal power of measured emissions vs. frequency.

At each frequency, before the data capture is made, an automated algorithm determines the receiver sensitivity to be used for the data capture. This algorithm works by performing a zero-span measurement and determining the received signal power. This received signal power level is then compared to the system noise power. If the signal power is less than a user-selectable lower bound, a certain amount (10 dB is the default)[16] greater than the system noise power level, the measurement system receiver sensitivity is increased by removing 10 dB of attenuation in the preselector step attenuator and a new zero-span measurement is captured. If the signal power is more than a user-selectable upper bound, a certain amount (35 dB is the default) greater than the system noise power level or if the signal causes an overload in the signal analyzer, the measurement receiver sensitivity is decreased by adding 10 dB of attenuation in the preselector step attenuator and a new zero-span measurement is captured. This process of adjusting the receiver sensitivity and then taking a new zero-span measurement continues until the received signal power is within the signal power lower and upper bounds defined above. Then, a data capture is collected. Note that the preselector step attenuator used in these measurements has a range of 0 to 60 dB.

The desired number of fixed frequency tuning steps between the start and stop frequencies is determined by the test operator. Spectrum analyzer parameters, such as the resolution bandwidth, detector type, sweep time, and attenuation, are also determined by the operator. The selection of sweep time, which determines the amount of time that data are collected at each fixed frequency in the stepped spectrum measurement (sometimes called dwell time), is particularly important. This dwell time must be sufficiently long enough to capture the maximum power output of the transmitter under test. Using a dwell time greater than necessary unduly lengthens the measurement and generates superfluous data.

[16] The effects of noise on a signal with signal power equal to or greater than 10 dB above the system noise power level are generally considered to be negligible. As the signal power decreases below 10 dB above the system noise power level, the effects of noise on the signal become increasingly more pronounced.

An important feature of the stepped spectrum measurement is the use of the automated, tunable YIG bandpass filter in the preselector used before the signal analyzer. The center frequency of this tunable bandpass filter is tuned to each fixed frequency before a zero-span measurement is captured at that fixed frequency. The main purpose of the tunable bandpass filter is to permit high sensitivity measurements of OOBE. This is accomplished by filtering out the high-power emissions from the transmitter when measuring out-of-band frequencies.

For each fixed frequency, the tunable bandpass filter greatly minimizes the potential for high power emissions at nearby frequencies to contaminate the stepped spectrum measurement. Without the filter, this contamination of the measurement is much more likely.

5. Measurement System Validation

To verify proper operation of the measurement system and to ensure accurate received signal power for the measurements, several measurement system characterizations were performed. Antenna gain for the measurement system RF antenna was measured prior to the measurement campaign. The measurement system dynamic range was also determined. Finally, tests were conducted to verify the stepped spectrum measurement operation including the correct tuning of the YIG bandpass filter and operation of the preselector step attenuator. Details of these characterizations are provided in this section.

5.1 Antenna Characterization

Antenna gain for the measurement system RF antenna was determined by measurements at ITS. The antenna gain measurements were made using the three-antenna method [7]. This method uses three different antennas (Antennas A, B, and C) to determine the gain of all three antennas. Antenna A (Penn Engineering 9030-1B15-NB) is a 15 dBi standard gain horn antenna used for the OOBE measurements. Antenna B (Microwave Engineering Corp. A390-710) is an E-plane sectoral horn antenna and Antenna C (Sage Millimeter SAO-2734030345-28-S1-WR) is an omnidirectional antenna. Antenna B and Antenna C were used in prior ITS mmWave propagation measurements [8].

Using this method, three separate transmission loss measurements were made in 10 MHz steps over the 26.5–40 GHz band: one using Antenna A to transmit and Antenna B to receive, one using Antenna A to transmit and Antenna C to receive, and one using Antenna B to transmit and Antenna C to receive. The measurements were conducted in a large open-area laboratory at ITS using an Agilent N5230A network analyzer. The antennas were mounted on non-conductive tripods so that they were 1 m above the floor with a 1 m horizontal separation between antennas. The horizontal separation ensures that the transmissions are easily in the far field.[17] The far field distance was determined from the omnidirectional antenna, since it has the largest aperture of the three antennas tested. Using the aperture of the omnidirectional antenna $D = 45.5\ mm$, the far field distance d (also known as the Fraunhofer distance) at 37.0 GHz is given as $d \geq 2D^2/\lambda = 0.51\text{m}$, where λ is the wavelength.

Time gating is used on the network analyzer to remove any reflections caused by the floor or other potential reflectors present in the room [9]. A time gate of 1.6 ns was chosen to remove these potential reflections and preserve the impulse response due to the direct ray. Use of this time gate captured the ringing that occurs in the antenna impulse response to more than 35 dB below the peak response. The results of the transmission loss measurements were then used to determine the gains of the three antennas as described in [7]. The resulting gain of the standard gain horn used as the measurement system RF antenna was computed to be 16.5 dBi at 37.0 GHz.

[17] The far field is where the radiated field appears to be planar in nature.

5.2 Measurement System Dynamic Range Characterization

The measurement system dynamic range characterization consisted of determining both the mean measurement system noise power level and the overload level. Knowing the mean measurement system noise power provides a way of discerning the reception of the mmWave gNodeB transmitted signals from noise when received signal power levels start to approach those of measurement system noise power levels. Additionally, knowing the level of received signals that cause the measurement system to overload is essential. Data obtained during overload conditions cannot be used since the true power level of the signal is not known when overload occurs because the signals are clipped by the signal analyzer. When clipping occurs, the true power level of the signal is lost since the signal analyzer reports a single, fixed maximum value for signal levels that are actually at or above the overload level. Overload can also introduce undesired, artificial signal components in the data, another compelling reason to avoid overload.

The measurement system dynamic range characterization is dependent on the settings that are used for the signal analyzer during the measurements. The signal analyzer settings that were used are provided in Section 7. These settings were experimentally determined to provide the maximum dynamic range for the overall measurement system. An approximately 1 dB better overall system NF (resulting in a slightly better sensitivity) could be obtained by using the internal preamp and LNA in the signal analyzer instead of the low noise path (LNP). However, the internal preamp and LNA were not used, because the signal level at which overload occurs is reduced by more than the 1 dB improvement in NF, resulting in a greatly reduced dynamic range. The signal analyzer's Flat Top resolution bandwidth filter with a 1 MHz resolution bandwidth was used for the OOBE measurements in this report.

The mean measurement system noise power was determined by first performing a noise diode calibration. The noise diode calibration used the traditional Y-factor method [10]. In this method, the calibration measurement is performed twice, once with the diode turned on and once with the diode turned off. The gain and NF are determined by *Y*, the difference between the measured power in dBm with the diode on and the measured power in dBm with the diode off. This calibration provided measurements of the preselector gain and system NF and furthermore was used to provide assurance that the measurement system was operating properly. The preselector gain was subtracted from the received power measured at the RF input of the signal analyzer to provide calibrated power measurements referenced to the antenna output. The mean measurement system noise power was determined from the NF and equivalent noise bandwidth (ENBW) of the resolution bandwidth filter[18] via

$$\begin{aligned} &Mean\ measurement\ system\ noise\ power \\ &= -174\ dBm + 10\log_{10}(ENBW) + NF. \end{aligned} \qquad (1)$$

[18] For the Flat Top resolution bandwidth filter in the Keysight N9042B signal analyzer used in the OOBE measurements in this report, the 1 MHz resolution bandwidth is the 3 dB bandwidth. The ENBW of this filter is very close to 1 MHz, specifically 1.0129 MHz.

Noise diode calibrations performed both in the laboratory and in the field revealed system NFs of approximately 14 to 16 dB depending on frequency.[19] This corresponds to a mean measurement system noise power of approximately −100 dBm to −98 dBm. The mean measurement system noise powers can be translated into peak values. For the purposes of this report, the peak noise power is defined as the noise power level exceeded 0.01% of the time. Since the measurement system noise is complex Gaussian noise, the peak noise power is 9.6 dB greater than the mean noise power [11]. Therefore, the peak measurement system noise power levels are −90.4 dBm to −88.4 dBm depending on frequency.

The measurement system overload level was determined as the signal power at the preselector antenna input that causes the signal analyzer to generate an analog-to-digital converter (ADC) overload error. For this characterization, the preselector step attenuator was set to 0 dB.[20] The measurement system was designed so that the signal analyzer will overload before the 1 dB compression point of the preselector LNA. The overload level was found by injecting a continuous wave (CW) signal at a test frequency of 38.55 GHz into the signal analyzer RF input. Starting at a low signal level presumed to be well below overload (−50 dBm), the signal power level at the signal analyzer RF input was slowly increased until ADC overload on the signal analyzer occurred. Overload occurred when the signal level at the signal analyzer RF input was increased above −14.7 dBm. Adjusting for the preselector gain (approximately 26.5 dB) provides the overload level at the antenna input to the preselector, −41.2 dBm. Note that this value corresponds to a step attenuation setting of 0 dB. When the maximum step attenuation is used (60 dB) the ADC overload occurs with an input signal level of +18.8 dBm.

While it is possible to compute a quantitative dynamic range value based on the ADC overload level and mean measurement system noise power, dynamic range can be defined in different ways. For example, dynamic range can be defined using mean measurement system noise power, peak measurement system noise power, a threshold set above either of these levels, the 1 dB compression point, or the ADC overload level. Therefore, the usefulness of a quantitative value for dynamic range is questionable and it is not given here. The bounds provided by ADC overload and mean and peak measurement system noise power level are entirely sufficient to characterize the useable dynamic range of the OOBE measurement system and therefore determine the range of received signal powers that can be input to the system.

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[19] Noise diode calibrations provide noise figure and preselector gain values that are referenced to the noise diode output of the preselector (see Figure 6, Section 3). However, since received signal power levels referenced to the antenna output of the measurement system receiver (see Figure 4, Section 3) are ultimately required, noise figure and preselector gain values are needed that are referenced to this antenna output. At 37 GHz, there is 0.5 dB more loss from the antenna output to the output of the preselector waveguide switch than from the noise diode output to the output of the preselector waveguide switch. Therefore, 0.5 dB must be subtracted from the preselector gain obtained from the noise diode calibration to reflect the true preselector gain from the antenna output to the RF input of the signal analyzer. The calibrated received power at the antenna output is then the measured received power from the signal analyzer minus the true preselector gain. Similarly, to obtain the overall system noise figure at the antenna output, 0.5 dB must be added to the overall system noise figure obtained from the noise diode calibration. Noise figure and received signal power values given in this report are those referenced to the antenna output.

[20] Of course, the measurement system overload level increases equally with increased attenuation from the preselector step attenuator.

5.3 Verification of the Stepped Spectrum Measurement Operation

Several tests were performed to verify the stepped spectrum measurement operation. First, to verify that the tuning of the YIG bandpass filter operated properly during a stepped spectrum measurement, a CW signal was generated at a given frequency within the frequency range of the stepped spectrum measurement and at a power level below the overload level and well above the noise floor (−50 dBm). For initial test purposes, the stepped spectrum measurement start frequency was set to 38.25 GHz and the stop frequency was set to 38.75 GHz. A CW signal at 38.55 GHz was generated with a Keysight M9384B vector signal generator. The signal was applied to the antenna input of the preselector in the measurement system, and the stepped spectrum measurement was initiated. The resulting measured data were processed, and the received signal power was compared to the input power. The signal power from the measured data was within ±0.5 dB of the input signal power. This test was repeated for CW input frequencies at the measurement band edges of this stepped spectrum measurement, namely at 38.25 GHz and 38.75 GHz. For these input frequencies, the signal power from the measured data was also within ±0.5 dB of the input signal power.

To test the operation of the preselector step attenuator, a process similar to the CW signal tests just described was followed. A CW signal at 38.55 GHz was generated with the Keysight M9384B vector signal generator, starting at an input signal power of −50 dBm. The signal was applied to the antenna input of the preselector in the measurement system, and the stepped spectrum measurement was initiated. The resulting measured data were processed. The received signal power was compared to the input power and the amount of step attenuation used in the measurement was noted.[21] After verification that the correct power was received and the step attenuation was confirmed to be correct, the signal power was increased by 10 dB, and the stepped spectrum measurement was repeated. This process of increasing the signal power in 10 dB increments, performing the stepped spectrum measurement, and verifying the signal power and attenuation levels was repeated for a few of the 10 dB steps of attenuation in the preselector step attenuator (attenuation levels of 20, 30, and 40 dB). Due to time constraints, only these attenuation levels were tested.

As a final test, a multitone signal was generated in MATLAB® and subsequently loaded onto the Keysight M9384B vector signal generator. The signal consisted of a set of equal amplitude sinusoidal tones spaced every 5 MHz over a 500 MHz bandwidth from 38.25 GHz to 38.75 GHz. The signal was applied to the antenna input of the preselector in the measurement system, and the stepped spectrum measurement was initiated. The resulting measured data were processed and compared to the input power over the 500 MHz bandwidth. The power in the measured data was within +2.0 / −0.3 dB of the expected input power over the entire 500 MHz bandwidth, indicating that the YIG bandpass filter tuning was working appropriately.

[21] The measurement control system software automatically stores the amount of step attenuation used at each frequency in the stepped spectrum measurement along with the measured data.

6. Measurement Setup and Procedure

For all the OOBE measurements performed in this study, the following general setup, operating, and data collection procedures were followed.

6.1 Cell Site and Measurement System Setup

The pointing device (described in Section 2.3) was first calibrated outdoors via the manufacturer's automated calibration procedure that runs on a separate, dedicated, wireless Android-based handset. The pointing device was then mounted on top of the mmWave gNodeB radio and adjusted so that the mmWave gNodeB radio and pointing device boresights pointed roughly west and were aligned as much as possible. The wireless handset received and displayed data from the pointing device, including boresight azimuthal angle (as referenced to true north), Latitude, Longitude, and Elevation.

The test cell site is normally kept in a standby state (called the locked state) where the eNodeB and mmWave gNodeB equipment is kept powered on, but the cell site is not operational and the eNodeB and mmWave gNodeB radios do not transmit. Before measurements commenced, the eNodeB and mmWave gNodeB were unlocked using the manufacturer's software.

The measurement vehicle was placed so that the measurement system receiver antenna was 30 ft. (≈ 9.1 m) west of the mmWave gNodeB radio, as shown in Figure 7. This ensured that the emissions measured with the measurement receiver were in the far field.

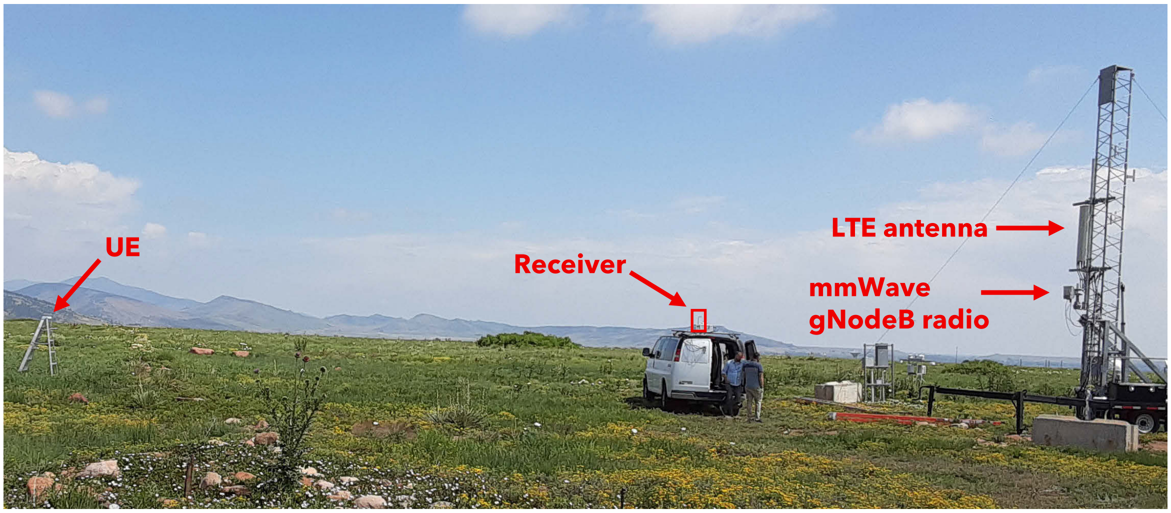

Figure 7. Location of the mmWave gNodeB radio mounted on the tower, measurement system vehicle, and UE. Credit: ITS Staff.

The far field distance was determined from the dimensions of the antenna array in the mmWave gNodeB radio that generates vertically polarized transmissions.[22] The height of the vertically polarized array is 135 mm with a width of 77 mm. This results in a diagonal distance of approximately 155 mm. Using the diagonal array dimension D = 155 mm, the far field distance d is given as $d \geq 2D^2/\lambda$, where λ is the wavelength. Therefore, for the OOBE measurements performed in this campaign at 37.05 and 37.2 GHz, the measurement system receiver antenna needs to be roughly at least 6.0 m from the mmWave gNodeB radio to be in the far field.

The height of the mmWave gNodeB radio was 3.6 m AGL; the height of the measurement receiver antenna was 2.6 m AGL. Because of this difference in height between the mmWave gNodeB radio and the measurement receiver antenna, some mechanical downtilt was employed at the mmWave gNodeB radio. Both the mechanical downtilt and the boresight azimuthal pointing angle of the mmWave gNodeB radio were adjusted to obtain a maximum signal power output from the mmWave gNodeB radio at the measurement system receiver antenna. The maximum signal power output was found by monitoring the mmWave gNodeB signal power with the Keysight FieldFox N9952B handheld microwave analyzer operating in the Over-the-Air 5G NR Mode while adjusting the downtilt and boresight azimuthal pointing angle.

[22]There is another antenna array in the mmWave gNodeB radio that generates horizontally polarized transmissions; it was not used in the computation of the far field distance.

The mmWave gNodeB radio tower parameters, including location coordinates, mechanical downtilt, and boresight azimuthal pointing angle used in these measurements were:

Latitude: 40.128053°
Longitude: −105.243711°
Mechanical downtilt: 4.9°
Boresight azimuthal pointing angle: 265.1°

A single UE was used to connect to the mmWave gNodeB and to receive data from the mmWave gNodeB. The UE was placed 54.5 ft. (≈ 16.6 m) west of the measurement receiver antenna and placed at a height of 4 ft. (≈ 1.2 m) AGL, as shown in Figure 7. The location of the UE was determined by finding the location as far west as practicable where the UE would be in the previously identified mmWave gNodeB radio antenna beam with the highest received signal power. The distance west of the measurement receiver antenna for the placement of the UE was limited by the downtilt of the mmWave gNodeB radio. A diagram showing the geometry of the OOBE measurement setup is given in Figure 8.

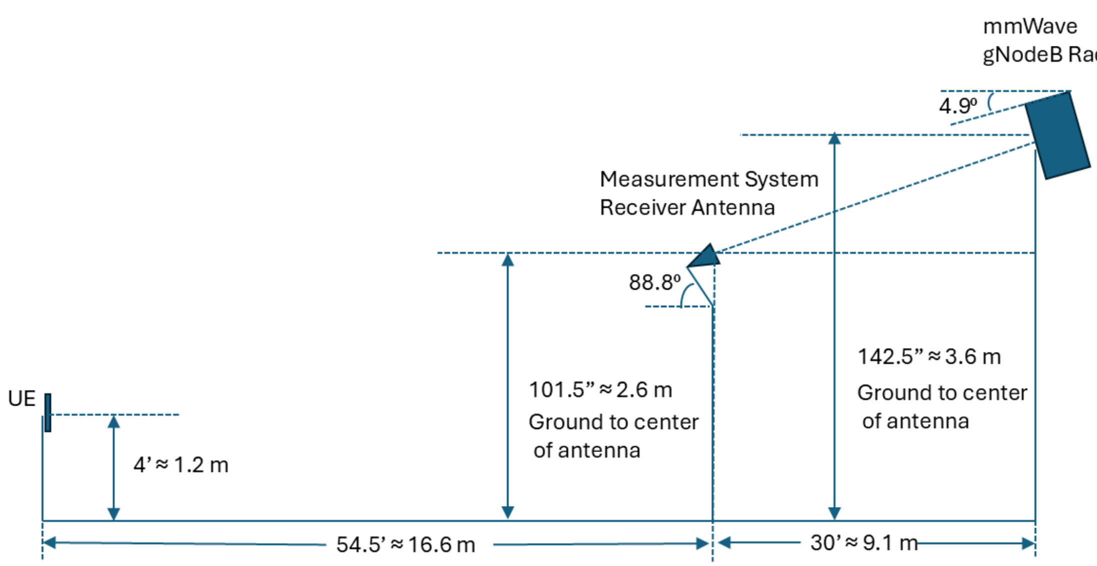

*Figure 8. Geometry of the mmWave OOBE measurement setup. * This drawing is not to scale, and the angles are exaggerated.*

The UE, a Samsung S23, was powered on and configured to operate only on LTE Band 66 and 5G mmWave Band n260. This UE band configuration limited the frequency bands the UE could operate on and prevented the UE from connecting to any cell sites in the area that may be operating on other bands. After the UE was configured to operate on the proper bands, it was placed into a Service Mode. In Service Mode the UE can display many 4G and 5G measurement parameters, such as Reference Signal Receive Power (RSRP), Reference Signal Receive Quality (RSRQ), Signal-to-Interference + Noise Ratio (SINR), Synchronization Signal Block (SSB) Index, etc. The 5G UE parameters were monitored to verify that expected received signal levels and quality were being met. For example, expected RSRP levels at the distance the UE was from the mmWave gNodeB are in the range of −65 dBm to −75 dBm and remained reasonably constant for the duration of the test. The SSB Index was monitored to determine on which antenna beam the UE was connected.

The testing performed for this report used the simplest case of a single UE that connected to the eNodeB and mmWave gNodeB. The mmWave gNodeB was configured to go into an idle state if no data were requested from the UE. Therefore, a client-server software application – one commonly used to make active measurements on IP networks, iPerf – was used during the OOBE measurements to send data traffic continuously in the downlink, i.e., from the mmWave gNodeB to the UE. The iPerf application can be configured to transmit either Transmission Control Protocol (TCP) or User Datagram Protocol (UDP) traffic. For these OOBE measurements, TCP was used. The iPerf software resided on a server that was connected to the core network located at the DoC Boulder Laboratories at 325 Broadway in Boulder, Colorado. An iPerf client application was installed on the UE and was used to configure the iPerf parameters and control the usage of iPerf. The iPerf application on the UE displayed the downlink throughput every second. Typical downlink throughput values ranged from 150 Mbps to 200 Mbps. These data rates were the maximum that ITS's current network can support. Occasionally, the data rates would fall below the 150 Mbps to 200 Mbps range.

These decreases in throughput were due to network congestion in the shared link between the core network located at the DoC Boulder Laboratories in Boulder and the Table Mountain test location approximately 15 km north of the DoC Boulder Laboratories campus.

6.2 Measurement Procedure

The OOBE measurement system equipment in the mobile measurement vehicle was powered on and allowed to warm up for at least 30 minutes. The measurement system control software was then used to initiate a measurement.

This software presented the user with a GUI to enter the desired stepped spectrum measurement parameters and signal analyzer settings listed in Section 7. Additionally, the user entered the filename and path for storing the output data.

The signal analyzer was configured to alert the user when it required an internal alignment. The user was notified of this on the GUI. Whenever this alert was received, the alignment procedure was initiated via a push-button control on the GUI. Performing this alignment procedure was required to maintain the accuracy of the measured received signal power in the signal analyzer to that specified by the manufacturer [12].

An initial noise diode calibration using the procedure described in Section 5.2 was then performed. This calibration provided a measurement of the preselector gain and system noise figure over the measurement operating frequencies. These results were used to confirm that the measurement system was operating properly. The preselector gain was used to provide calibrated power measurements referenced to the measurement system RF antenna output.

A stepped spectrum measurement was then initiated over the frequency range specified by the user and the measurement was conducted automatically under software control. After the measurement concluded, the mmWave gNodeB transmitter and UE were powered down. Another stepped spectrum measurement was then performed to characterize the over-the-air background noise at the measurement system receiver.

7. Out-of-Band Emissions Measurements in the 36–37 GHz Band

OOBE measurements in the 36–37 GHz band were conducted in June 2025 following the procedure described in Section 6.2. For the 36–37 GHz OOBE measurements performed in this study, the stepped spectrum measurement and signal analyzer parameters shown below were used.

Measurement Parameters
Start Frequency: 36.0 GHz
Stop Frequency: 37.3 GHz
Frequency Step Size: 1 MHz
Number of Frequency Steps: 1300
Number of Frequency Points: Number of Frequency Steps + 1 = 1301
Signal Power Lower Bound: 10 dB greater than the system noise power level
Signal Power Upper Bound: 35 dB greater than the system noise power level

Signal Analyzer Parameters
Resolution Bandwidth: 1 MHz
Resolution Bandwidth Filter Type: Flat Top
Video Bandwidth: 50 MHz (no video filtering)
Detector Type: Positive Peak
Sweep Time: 500 ms
Number of Sweep Points: 1001
Attenuation: 0 dB
Microwave Path: Low Noise Path
Internal Preamp: Off
Low Noise Amplifier: Off
Noise Floor Extension: Off

The stepped spectrum measurements were performed first using a mmWave gNodeB radio center frequency of 37.05 GHz and then repeated using a center frequency of 37.2 GHz. The run time required for the stepped spectrum measurement at each center frequency was approximately 28 minutes. Figure 9 and Figure 10 show the measured *peak* power of the mmWave gNodeB at the measurement system receiver antenna output in a 1 MHz resolution bandwidth for both center frequencies 37.05 and 37.2 GHz, respectively. Measured over-the-air background noise is also shown in these figures.

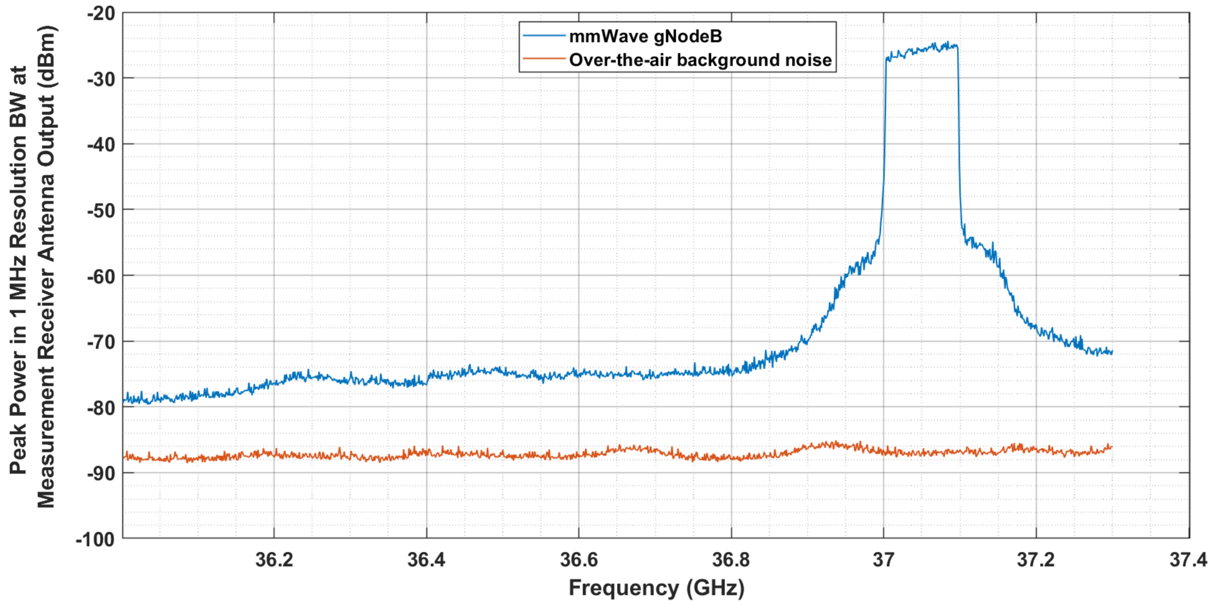

Figure 9. Measured peak power as a function of frequency of the mmWave gNodeB operating at 37.05 GHz and over-the-air background noise at the measurement system receiver antenna output in a 1 MHz resolution bandwidth.

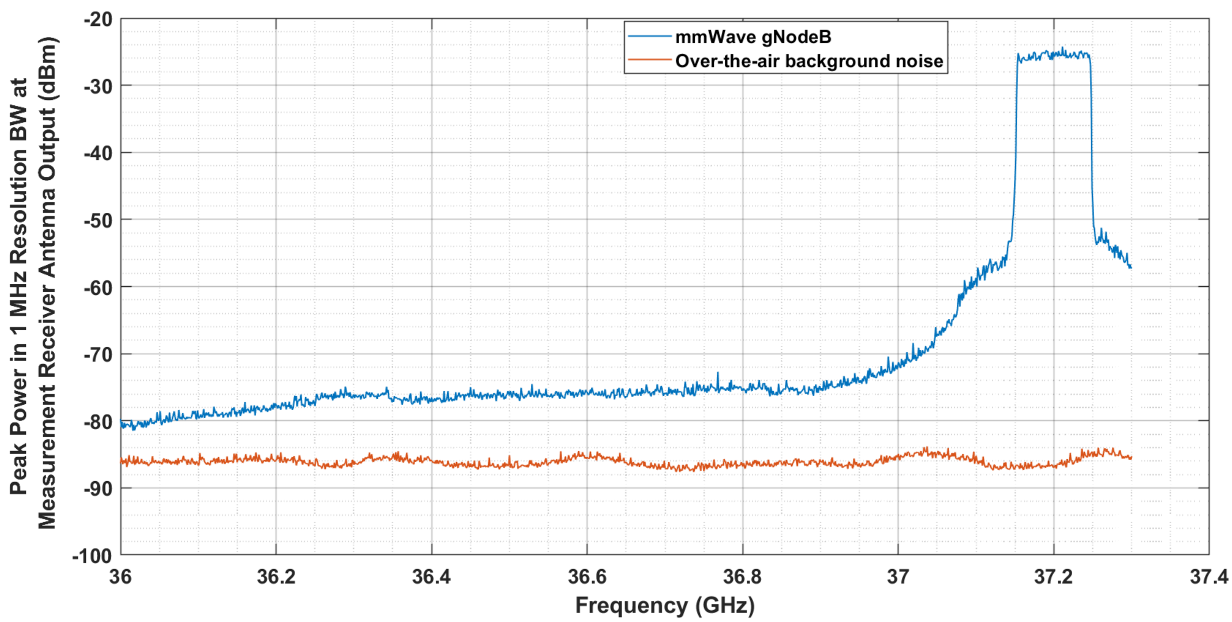

Figure 10. Measured peak power as a function of frequency of the mmWave gNodeB operating at 37.2 GHz and over-the-air background noise at the measurement system receiver antenna output in a 1 MHz resolution bandwidth.

8. Determination of Effective Isotropic Radiated Power

The basic link budget equation can be derived from a model of a radio transmitter and a radio receiver separated in distance by a radio propagation channel. Figure 11 shows this model. From this model, an equation for determining P_r, the received signal power in dBm, is obtained as

$$P_r = P_t + G_t - L_b + G_r , \tag{2}$$

where P_t is the transmitter power in dBm, G_t is the transmitter antenna gain in the direction of the receiver in dBi, L_b is the basic transmission loss between the transmitter antenna and the receiver antenna in dB, and G_r is the receiver antenna gain in dBi.

Rearranging (2) in terms of $P_t + G_t$ provides an expression of the transmitter EIRP in dBm,

$$EIRP\ (dBm) = P_t + G_t = P_r - G_r + L_b . \tag{3}$$

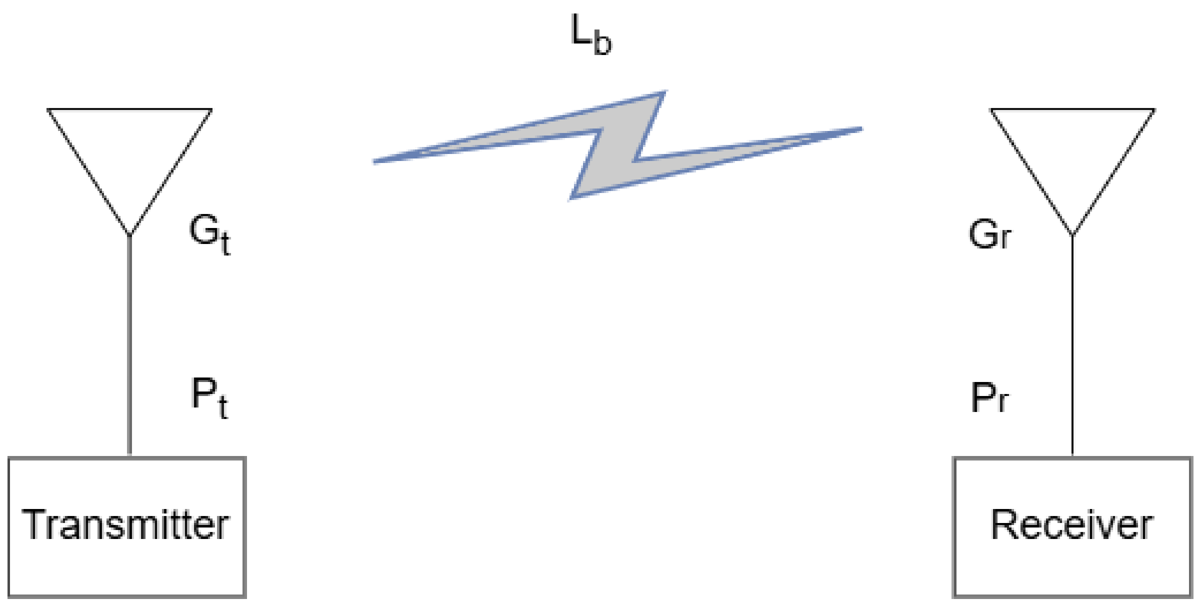

Figure 11. Model showing the radio propagation channel between a transmitter and receiver.

The received signal power P_r, for center frequencies of 37.05 GHz and 37.2 GHz, is shown in Figure 9 and Figure 10, respectively.

For our measurements, the basic transmission loss L_b is approximated by the theoretical free space loss L_{bfs}. The measurements of the received signal power P_r were made under conditions where the free space loss was considered to be a reasonable approximation of the expected basic transmission loss L_b. Therefore, L_b is given as

$$L_b(dB) = L_{bfs}(dB) = \{20 \log_{10} f(GHz) + 20 \log_{10} d_{3D}(m) + 32.4\}\,, \quad (4)$$

where L_b is given in terms of decibels, f is the frequency in GHz, and d_{3D} is the three-dimensional distance between the transmitter and receiver antennas in meters [13].[23] Since the transmitter center frequencies are 37.05 GHz and 37.2 GHz, and the distance between the transmitter and receiver is 30 ft. (≈ 9.1 m), $L_b \approx 83.0$ dB. Given the measured receiver antenna gain $G_r = 16.5$ dBi (see Section 5.1),

$$EIRP\ (dBm) = P_t + G_t = P_r - G_r + L_b = P_r + 66.5\,. \quad (5)$$

Therefore, applying (5) to the received signal powers from the mmWave gNodeB transmissions shown in Figure 9 and Figure 10, provides the *peak* transmitter EIRP shown in Figure 12 and Figure 13.

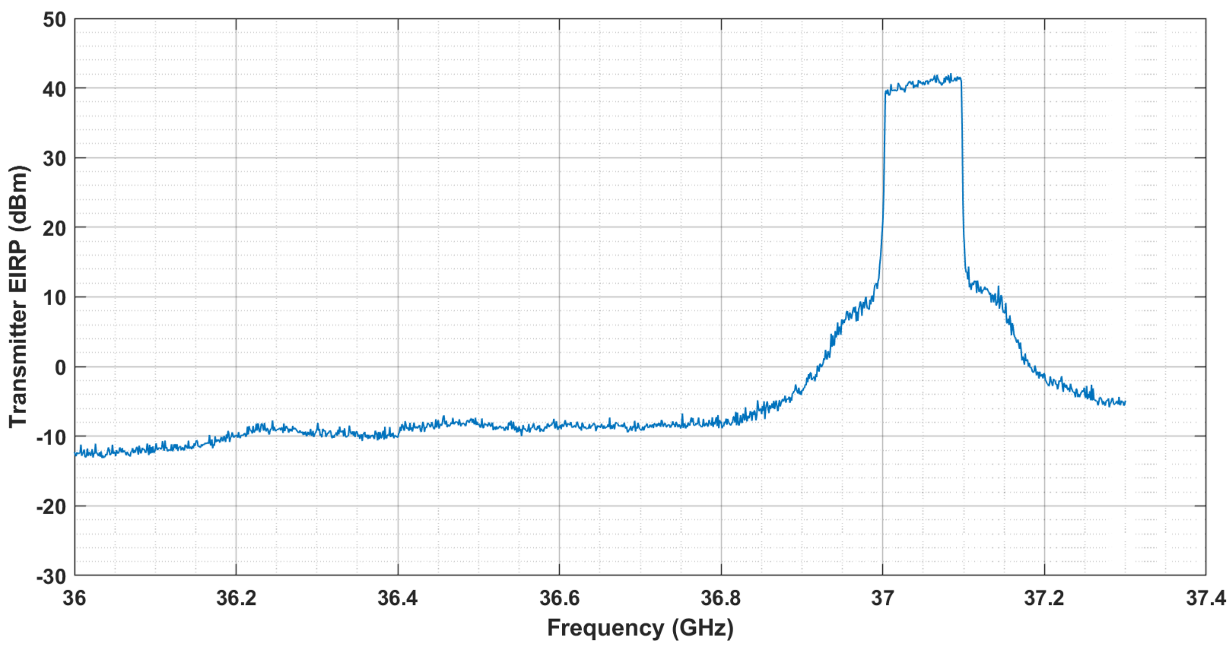

Figure 12. Peak EIRP as a function of frequency of mmWave gNodeB transmission at a center frequency of 37.05 GHz in a 1 MHz resolution bandwidth.

[23] The distance between the transmitter and receiver d_{3D} used in the computation of L_b ideally should be the three-dimensional distance between the transmitter antenna and the receiver antenna, taking into consideration the antenna heights AGL and elevations of the transmitter and receiver. However, in this specific case, the difference between the three-dimensional distance and the two-dimensional distance is negligible and the two-dimensional distance is used.

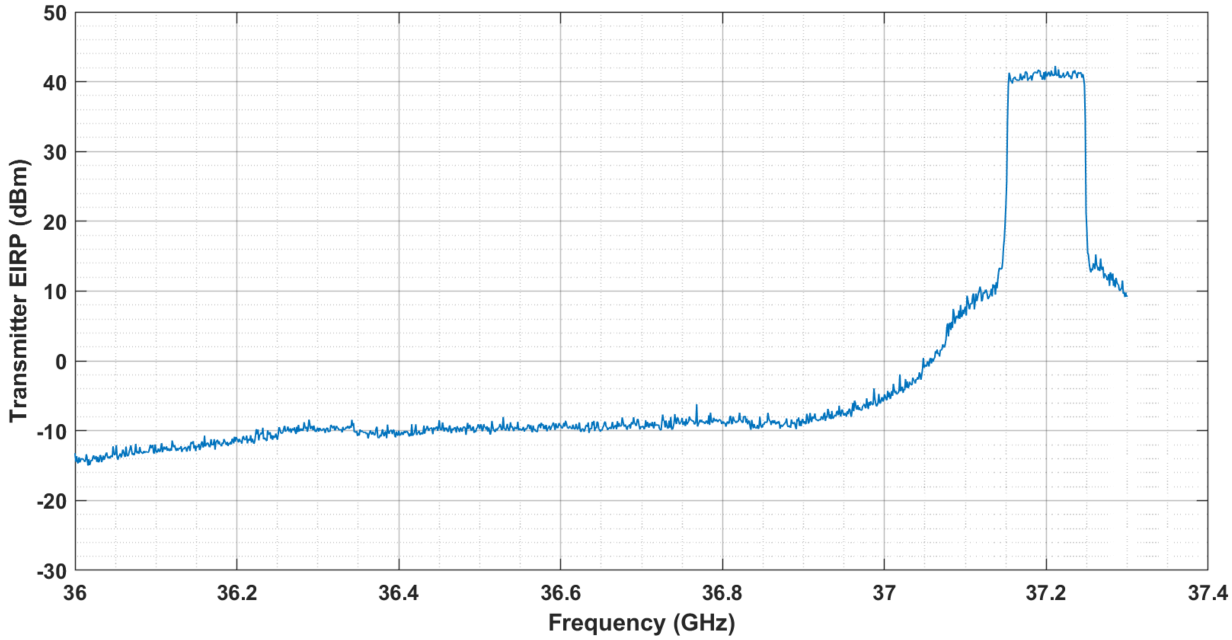

Figure 13. Peak EIRP as a function of frequency of mmWave gNodeB transmission at a center frequency of 37.2 GHz in a 1 MHz resolution bandwidth.

As seen in Figure 12 and Figure 13, the measured in-band *peak* transmitter EIRP for the mmWave gNodeB radio in a 1 MHz resolution bandwidth was approximately +40 dBm to +42 dBm. Emissions outside of the 100 MHz channel generally decrease monotonically, as expected. For the mmWave gNodeB operating at a center frequency of 37.05 GHz, the steep transition from in-band to out-of-band occurs right at 37 GHz, the upper edge of the 36–37 GHz band. The *peak* OOBE at 36 GHz, the lower edge of the 36–37 GHz band, is approximately −12 dBm.

For the mmWave gNodeB radio operating at a center frequency of 37.2 GHz, the maximum OOBE at 37 GHz, the upper edge of the 36–37 GHz band, is approximately −6 dBm. The *peak* OOBE at 36 GHz, the lower edge of the 36–37 GHz band, is approximately −14 dBm.

Figure 14 shows a plot of the *peak* EIRP for the mmWave gNodeB operating at both the 37.05 and 37.2 GHz center frequencies with the center frequencies normalized to 0 Hz. This provides for an easier comparison of the spectral emissions from both cases. Note that the shape of the responses is very close in general. For more than 95% of the normalized frequency values, the peak EIRP values are within ± 2.0 dB. The transmission at the 37.2 GHz center frequency shows a flatter in-band frequency response.

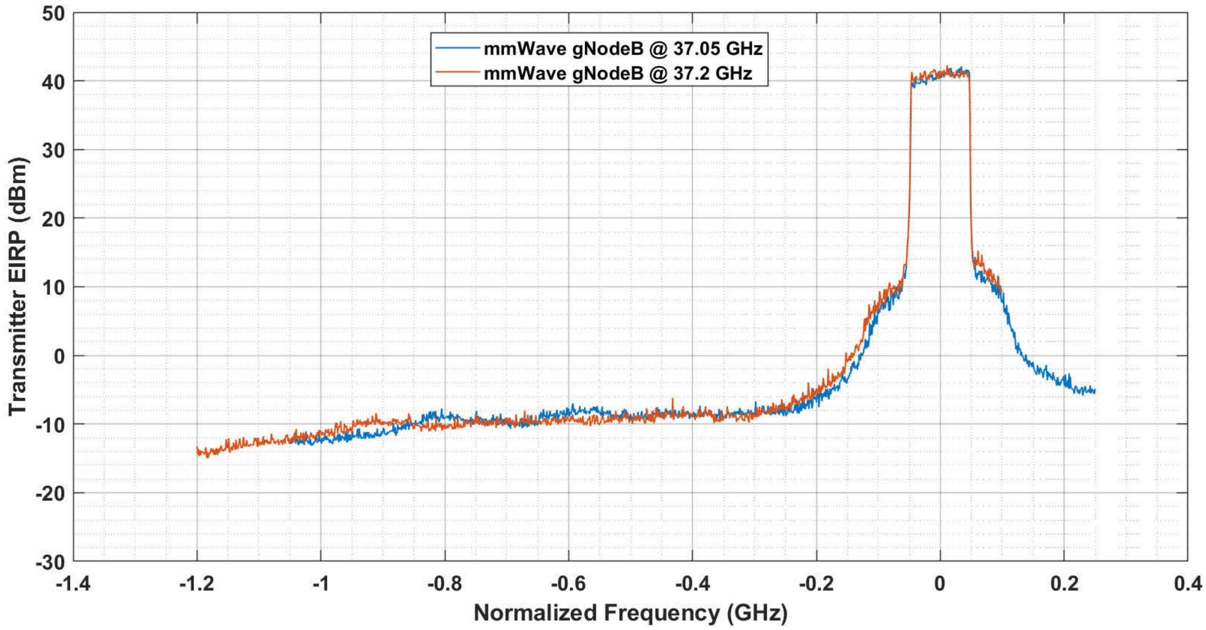

Figure 14. Peak EIRP as a function of normalized frequency of mmWave gNodeB transmission at center frequencies of 37.05 and 37.2 GHz in a 1 MHz resolution bandwidth.

9. Additional Measurements Showing Out-of-Band Emissions at Frequencies below 36 GHz

OOBE measurements showing emissions at frequencies below 36 GHz in addition to those in the 36–37 GHz band were performed in July 2025, on the outdoor mmWave gNodeB described in Section 2 of this report. For these measurements, the signal analyzer parameters used were the same as those listed in Section 7. The measurement parameters used are given below.

Start Frequency: 33.5 GHz
Stop Frequency: 37.2 GHz
Frequency Step Size: 1 MHz
Number of Frequency Steps: 3700
Number of Frequency Points: Number of Frequency Steps + 1 = 3701
Signal Power Lower Bound: 10 dB greater than the system noise power level
Signal Power Upper Bound: 35 dB greater than the system noise power level

For these measurements, the mmWave gNodeB was set to a center frequency of 37.05 GHz. Figure 15 shows the measured *peak* power of the mmWave gNodeB at the measurement system receiver antenna output in a 1 MHz resolution bandwidth. Emissions from the mmWave gNodeB above the noise floor are seen even down at 33.5 GHz.

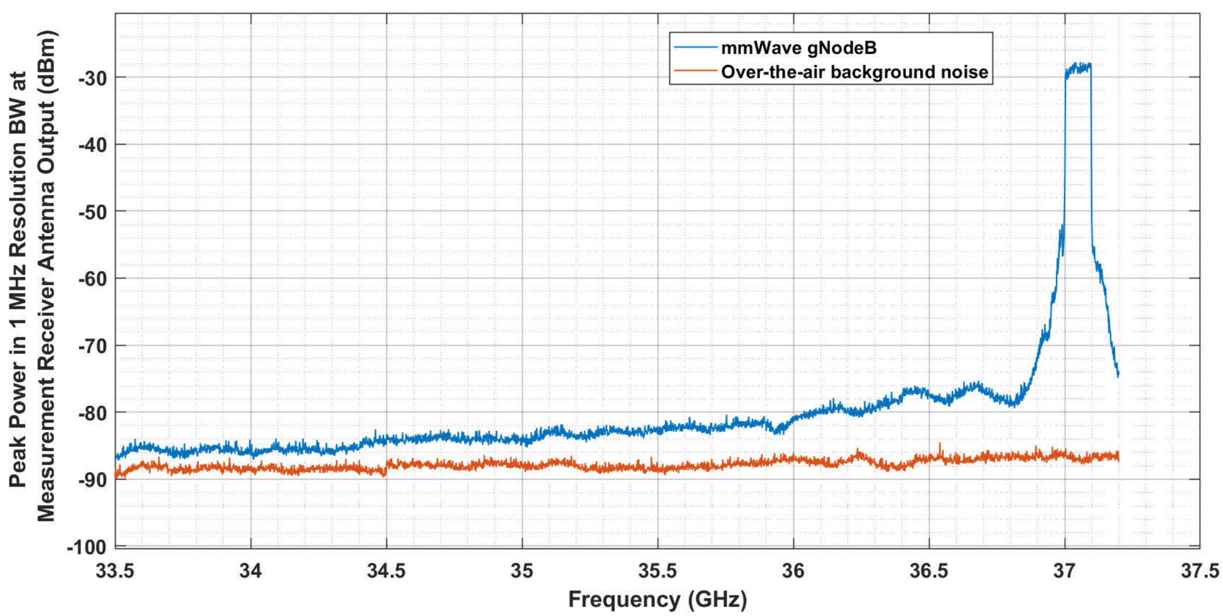

Figure 15. Measured peak power as a function of frequency from 33.5 GHz to 37.2 GHz of the mmWave gNodeB operating at 37.05 GHz and over-the-air background noise at the measurement system receiver antenna output in a 1 MHz resolution bandwidth.

Applying (5) to the received signal power from the mmWave gNodeB transmission shown in Figure 15 provides the *peak* transmitter EIRP shown in Figure 16.

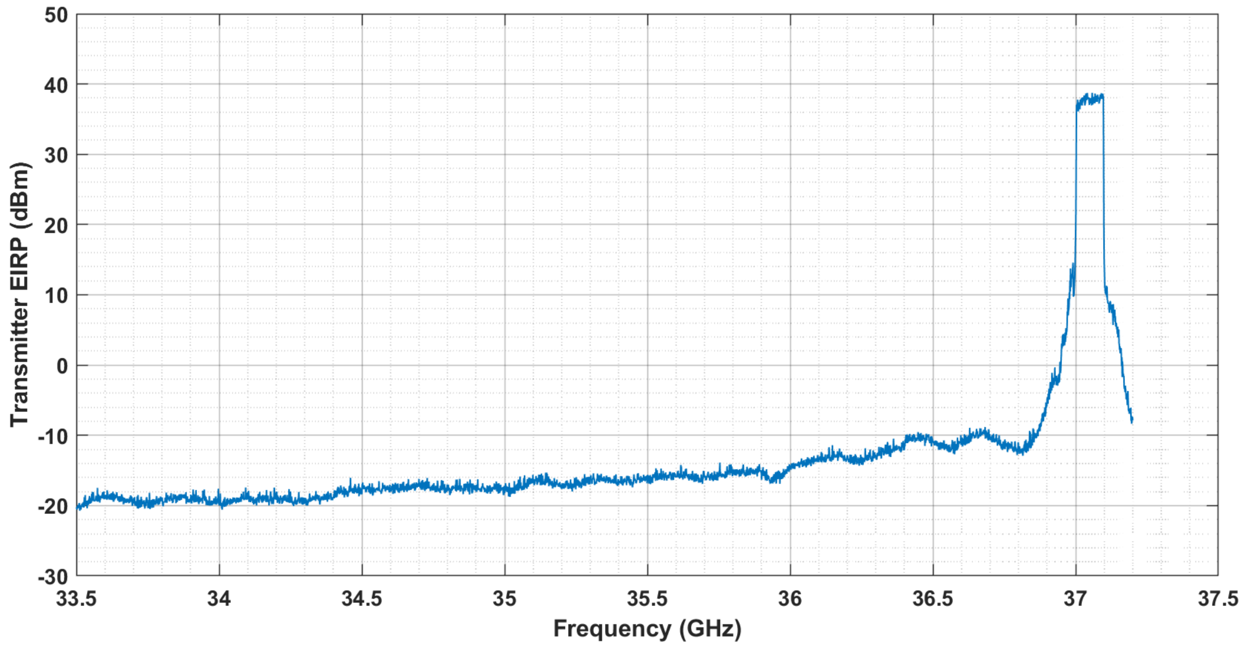

Figure 16. Peak EIRP as a function of frequency from 33.5 to 37.2 GHz of mmWave gNodeB transmission at a center frequency of 37.05 GHz in a 1 MHz resolution bandwidth.

Note that the emissions do continue to decrease in power very gradually as a function of decreasing frequency below 36 GHz. Also note that the *peak* in-band measured power and the peak out-of-band measured power in the 36–37 GHz band are slightly lower than those measured in the previous measurements performed in June 2025 (see Figure 9 and Figure 12). It is not definitively known why this occurred.

10. Potential Method to Approximate Total Radiated Power in Out-of-Band Emissions Based on Effective Isotropic Radiated Power Measurements

Total radiated power (TRP) is sometimes used instead of EIRP in specifying emissions limits. For example, the emissions limits specified in ITU Resolution 243 [2] for unwanted emissions into the 36–37 GHz band are given as TRP.

The methodology specified by the FCC for measuring TRP is detailed in [14]. The FCC methodology essentially makes a series of EIRP measurements at equally spaced azimuthal, elevation, and, in some cases, roll angles from the device under test, both for vertical and horizontal polarizations, and averages the EIRP measurements to obtain the TRP. Measurements of TRP using this methodology are challenging in practice and typically would be carried out in an anechoic chamber with specialized equipment positioners. Measurement of TRP using this methodology is further complicated for devices under test such as a cellular system comprising both a base station and UEs. Placing the base station in a test operating mode where it uses a 3GPP test model [15] designed for conformance testing eliminates the requirement of having UEs for the base station to transmit and can be used to simplify TRP testing. However, the test operating mode may not exactly emulate a cellular system operating in its normal mode, which is a known risk of using this technique.

The concept of TRP is particularly useful when the device under test has an integrated antenna, i.e., the radio transmitter and the antenna are not separable, and this is not uncommon in mmWave devices. The transmitter output ports are not accessible in such a case; therefore, a direct measurement of transmitter output power is not possible. TRP is useful when the device under test has an integrated antenna because strictly radiated measurements provide the TRP, and TRP is equivalent to transmitter output power.[24]

A potential, very simple method of approximating TRP in OOBE is presented here based on a single EIRP measurement at one angle, in lieu of multiple EIRP measurements at different angles, from the device under test.

The method is based on two assumptions. First, as stated in Section 1, the output power of the transmitter is specified by the manufacturer to be nominally +29 dBm into each of two antenna arrays[6] in a *100 MHz bandwidth*. Note that this is an *average* power, whereas the EIRP measured power results in this paper are *peak* power values. Since the output power spectrum of the transmitted signal is fairly flat (varies less than ±1.4 dB) over the *100 MHz bandwidth*, and the power of the transmitted signal is mostly contained in the *100 MHz bandwidth*, the in-band output power (into each of two antenna arrays) is equivalent to approximately +9 dBm in a *1 MHz bandwidth*. Therefore, the total in-band output power is the sum of the powers into each antenna array which is +12 dBm in a *1 MHz bandwidth*. Since

[24] TRP is the radiated power in all directions from a source and therefore can be considered as the transmitter power of the source being applied to an isotropic radiator [16]. Therefore, TRP is equal to the transmitter power of the source plus the gain of the isotropic radiator. Since gain of the isotropic radiator is 0 dBi, TRP is equal to the transmitter power of the source.

TRP is equivalent to the output power of the transmitter, the in-band TRP is also +12 dBm in a *1 MHz bandwidth*. Note that this in-band TRP is an *average* power value.

The next step in determining the OOBE in terms of TRP is based on an assumption that the shape of the magnitude response (power as a function of frequency) is the same for both the EIRP measurement and TRP. Inherent in this assumption is the simplification that the transmitter antenna gain remains the same over the frequency range of the measurement. Any potential transmitter antenna gain variation with frequency is not accounted for. This process results in converting the *peak* EIRP measured data shown in Figure 12 and Figure 13 to produce "inferred" *average* TRP data.

For example, in Figure 13, the maximum EIRP is found (approximately 42 dBm). A conversion factor is determined by subtracting the in-band TRP (+12 dBm in a *1 MHz bandwidth*) from the maximum EIRP. Therefore, for this example, the conversion factor is 30 dB. The inferred TRP, as a function of frequency, is found by subtracting the conversion factor from the EIRP vs. frequency plot. In this example, the inferred TRP is determined by subtracting 30 dB from the EIRP vs. frequency plot in Figure 13. Note that the resulting inferred TRP values vs. frequency are *average* power values.

Plots of inferred TRP in a *1 MHz bandwidth*, derived from the *peak* EIRP measured data as discussed above, are given in Figure 17 and Figure 18.

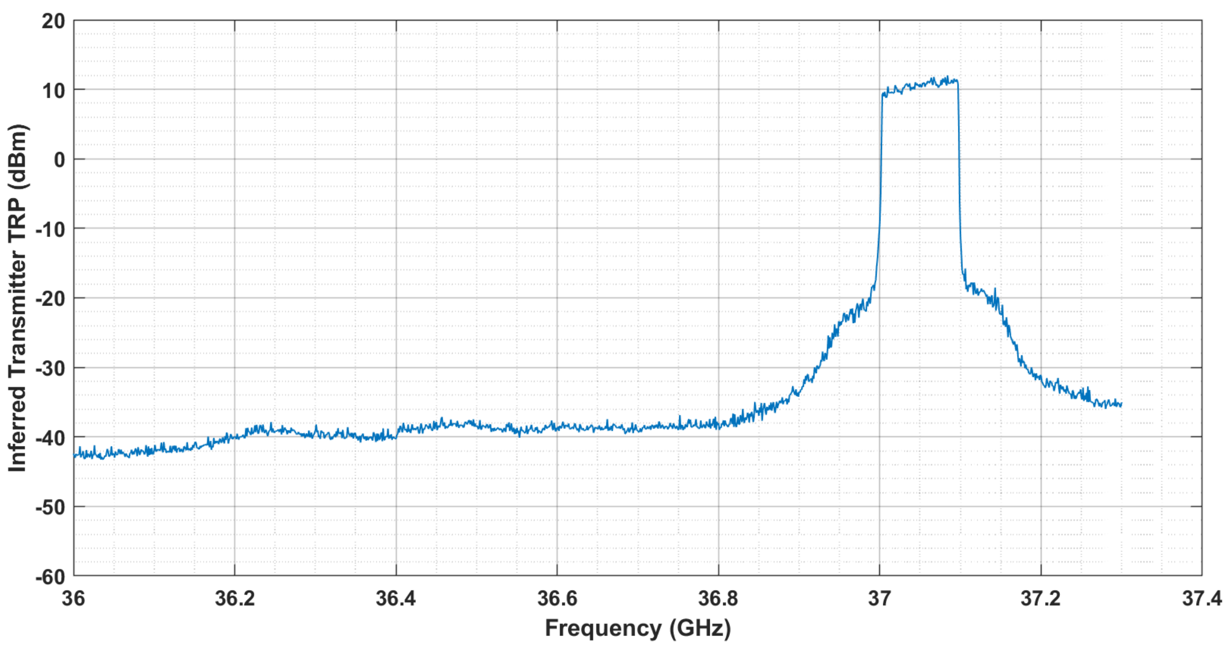

Figure 17. Inferred TRP as a function of frequency of mmWave gNodeB transmission at a center frequency of 37.05 GHz in a 1 MHz resolution bandwidth.

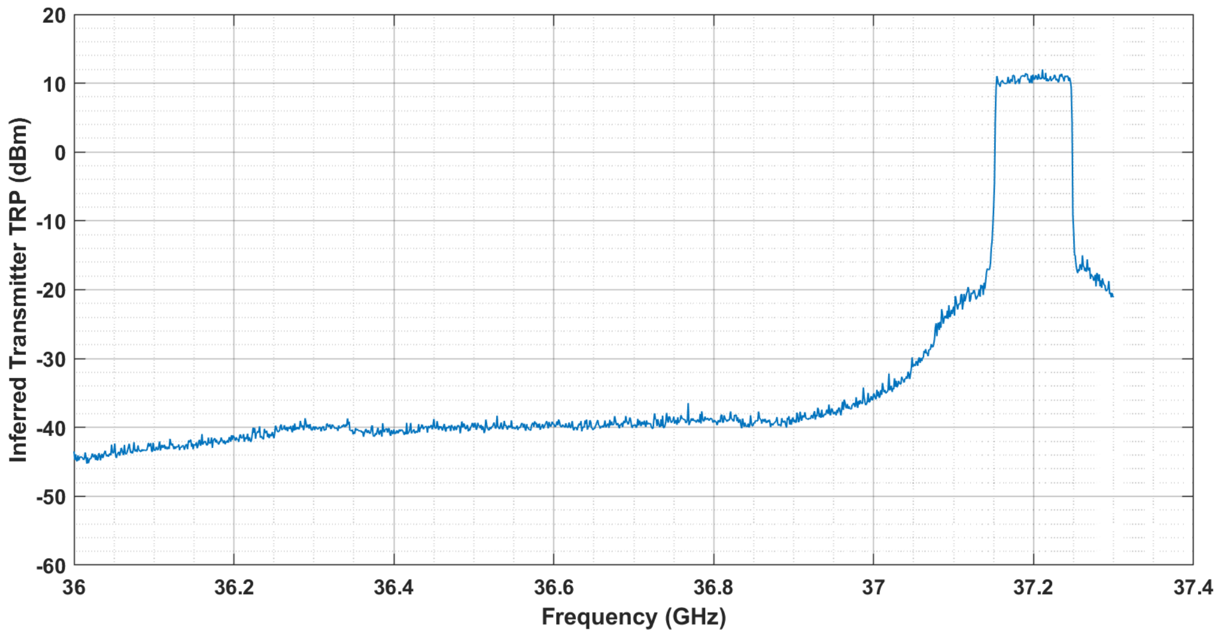

Figure 18. Inferred TRP as a function of frequency of mmWave gNodeB transmission at a center frequency of 37.2 GHz in a 1 MHz resolution bandwidth.

11. Comparison of ITS Measurements with ITU Resolution 243 Specifications for Unwanted Emissions in the 36–37 GHz Band

In this section, the results of the OOBE measurements performed by ITS are compared with the ITU Resolution 243 transmitter specifications for unwanted emissions into the 36–37 GHz band. These specifications, provided in Table 1 of ITU Resolution 243, define the unwanted emission mean power limit for the 36–37 GHz band as −23 dBW/GHz and the recommended limit as −30 dBW/GHz. These limits are based on TRP.

Initially, *average* EIRP values derived from ITS measurements were compared to the ITU Resolution 243 specifications. Then inferred TRP values were calculated from ITS measurements and compared to ITU Resolution 243 specifications. Note that inferred TRP values are *average* power values as explained in Section 10.

11.1 Conversion of Measured Data from Peak to Average Power

The measurements performed by ITS were *peak* EIRP measurements. EIRP measurements were performed at two different frequencies, 37.05 GHz and 37.2 GHz. ITU Resolution 243 specifications are based on mean (or *average*) power. Research into peak-to-average power ratios (PAPRs) of 5G orthogonal frequency division multiplexing (OFDM) signals revealed PAPRs are typically in the 8–12 dB range [17]. Processing a small example in-phase and quadrature (IQ) data capture of the mmWave gNodeB downlink signal used for the OOBE measurements in this study, a PAPR of approximately 10.6 dB was found. Since PAPRs are typically in the 8–12 dB range for 5G OFDM signals, and ITS measurements showed an example PAPR of approximately 10.6 dB, a 10 dB PAPR was chosen to convert the *peak* EIRP measurements to *average* EIRP measurements. The *average* EIRP is found by subtracting the PAPR from the *peak* EIRP.

For the measurement performed at each of the two frequencies, the *peak* EIRP data were loaded into MATLAB® for subsequent processing. The *peak* EIRP values over the 36–37 GHz band were then extracted from the data. These 36–37 GHz *peak* EIRP values were in dBm. Subtracting the PAPR of 10 dB from the *peak* EIRP values then provided *average* EIRP values in dBm. Next, the *average* EIRP values were converted to linear EIRP values in mW and then summed. The sum of the *average* linear values is the *average* EIRP integrated channel power in mW in the 1 GHz bandwidth from 36–37 GHz. This was converted back to dBm and then converted to dBW. This results in the *average* EIRP integrated channel power in dBW/GHz in the 36–37 GHz band and can then be compared to the ITU Resolution 243 specifications.

11.2 Average EIRP Integrated Channel Power Measurements vs. ITU Resolution 243 Specifications

For the signal centered at 37.05 GHz, using the *peak* EIRP data in Figure 12, the *average* EIRP integrated channel power in the 36–37 GHz band was calculated to be −10.5 dBW/GHz. This level exceeds the unwanted emission mean power limit for International Mobile Telecommunications (IMT) stations of −23 dBW/GHz for the 36–37 GHz band.

For the signal centered at 37.2 GHz, using the *peak* EIRP data in Figure 13, the *average* EIRP integrated channel power in the 36–37 GHz band was calculated to be −19.6 dBW/GHz. This level also exceeds the unwanted emission mean power limit for IMT stations of −23 dBW/GHz for the 36–37 GHz band.

Therefore, the calculated *average* EIRP values based on the ITS *peak* EIRP measurements of the mmWave gNodeB do not meet the ITU Resolution 243 specifications in the 36–37 GHz band.

Table 1 displays the *average* EIRP integrated channel power results vs. the ITU Resolution 243 specifications for unwanted emissions into the 36–37 GHz band. The table also shows whether the results are below the ITU Resolution 243 limits or not.

Table 1. Average EIRP integrated channel power vs. ITU Resolution 243 specifications.

Operating Frequency	Average EIRP Integrated Channel Power	ITU Resolution 243 Unwanted Emission Mean Power Limit	Below Limit	ITU Resolution 243 Recommended Limit	Below Limit
37.05 GHz	−10.5 dBW/GHz	−23 dBW/GHz	No	−30 dBW/GHz	No
37.2 GHz	−19.6 dBW/GHz	−23 dBW/GHz	No	−30 dBW/GHz	No

11.3 Inferred TRP Integrated Channel Power Measurements vs. ITU Resolution 243 Specifications

In Section 10, the inferred TRP was calculated by subtracting a 30 dB conversion factor from the *peak* EIRP vs. frequency plot. Note that inferred TRP values are *average* power values, as explained in Section 10.

For the first step in determining the inferred TRP integrated channel power, the 30 dB conversion factor was subtracted from each *peak* EIRP measurement point.[25] Similar to the process followed for the EIRP integrated channel power calculation, the power values in dBm were converted to linear values in mW and then summed across the 36–37 GHz range. This resulted in the inferred TRP integrated channel power in mW in the 1 GHz bandwidth from 36–37 GHz. The inferred TRP integrated channel power in mW was converted to the

[25] Each measurement point in the peak EIRP measured data represents the peak power in dBm in a 1 MHz resolution bandwidth.

equivalent value in dBW. This results in the inferred TRP integrated power in dBW/GHz and can then be compared to the ITU Resolution 243 specifications.

For the signal centered at 37.05 GHz, using the inferred TRP data in Figure 17, the inferred TRP integrated channel power in the 36–37 GHz band was calculated to be −30.5 dBW/GHz. This level is below the unwanted emission mean power limit for IMT stations of −23 dBW/GHz for the 36–37 GHz band and is also slightly below the recommended limit of −30 dBW/GHz for the 36–37 GHz band.

For the signal centered at 37.2 GHz, using the inferred TRP data in Figure 18, the inferred TRP integrated channel power in the 36–37 GHz band was calculated to be −39.6 dBW/GHz. This level is below the unwanted emission mean power limit for IMT stations of −23 dBW/GHz for the 36–37 GHz band and is also below the recommended limit of −30 dBW/GHz for the 36–37 GHz band.

Therefore, the inferred TRP values of the mmWave gNodeB meet the ITU Resolution 243 specifications in the 36–37 GHz band.

Table 2 displays the inferred TRP integrated channel power results vs. the ITU Resolution 243 specifications for unwanted emissions into the 36–37 GHz band. The table also shows whether the results are below the ITU Resolution 243 limits or not.

Table 2. Inferred TRP integrated channel power vs. ITU Resolution 243 specifications.

Operating Frequency	Inferred TRP Integrated Channel Power	ITU Resolution 243 Unwanted Emission Mean Power Limit	Below Limit	ITU Resolution 243 Recommended Limit	Below Limit
37.05 GHz	−30.5 dBW/GHz	−23 dBW/GHz	Yes	−30 dBW/GHz	Yes
37.2 GHz	−39.6 dBW/GHz	−23 dBW/GHz	Yes	−30 dBW/GHz	Yes

12. Comparison of ITS Measurements with Other Measurements

The measured power values for the ITS OOBE measurements in this report are *peak* power values, specifically the maximum value observed over the duration of the sweep time at each frequency of the stepped spectrum measurement. ITS prefers using peak power measurements when measuring complex waveforms, such as 5G TDD signals, since averaging can provide misleading results. Averaging always requires defining a specific time window over which the averaging will be computed. The choice of time window is critical, and improper choice may lead to incorrect average power measurements that are lower or higher than the true average power. Peak power measurements avoid this issue, although the dwell time of the chosen peak measurement must be long enough to capture the true peak of the signal.

In general, comparison of *peak* power values and *average* power values for complex waveforms is not trivial. Peak power can be defined in different ways. Peak power can be defined as the maximum value over a given time period, or it can be defined as a threshold in which power values are exceeded for a given percentage of the time. Furthermore, different percentages of time can be chosen. Average power can be computed over different time periods and in complex waveforms such as the 5G TDD signals used in the mmWave gNodeB, the averaging can take place while the signal is behaving in different ways. For example, does the averaging occur over the time period when the SSBs and the data are being transmitted or does the averaging occur only when the data are being transmitted? As another example, in a measurement of downlink power, the averaging could only be taken over downlink transmissions and not include uplink transmissions. Conversely, the averaging could be taken to include both downlink and uplink transmissions. Note that it may be challenging to ensure that averaging does not include uplink transmissions when measurements are being performed in the frequency domain, i.e., for spectrum measurements. Proper application of gated sweeps can be used to solve this problem.

It is very important to carefully define and specify how the measured values are obtained to provide meaningful measurements and comparisons of measurements.

The NF of any measurement system is an important consideration when performing highly sensitive measurements such as OOBE measurements. The measured NF of the ITS mmWave stepped spectrum measurement system was measured to be within 14 to 16 dB.

OOBE measurements could be performed with the mmWave gNodeB operating in test modes using 3GPP test models. Operating in these test modes, the mmWave gNodeB transmits pseudorandom noise (PN) code signals with different modulations without using any UEs. ITS measurements of RF Power Output and OOBE on the mmWave gNodeB were performed with the mmWave gNodeB operating in a realistic mode with a single UE forming a very simple cell site.

Also, RF Power Output and OOBE measurements could be performed in an anechoic chamber. ITS measurements of RF Power Output and OOBE were performed in an open outdoor environment free of obstructions at the ITS test cell site at Table Mountain (see Section 2). While some possibility of ground reflections exist in the ITS test setup, the potential for ground reflections is greatly minimized by the geometry of the measurement, limited elevation beamwidth of the measurement system horn antenna, and the selection of the mmWave gNodeB beamset where the lowest elevation angle antenna beams are focused just slightly below the horizon and most of the beams are focused in elevation well above the horizon.

13. Summary

The FNPRM in FCC WT Docket No. 24-243 requests comments on revising the emissions limits for Upper Microwave Flexible Use Service operations above 37 GHz to protect passive sensors in the adjacent 36–37 GHz band. As one possibility, the FCC is considering adopting the emissions limits specified in ITU Resolution 243.

To provide input for the FNPRM, OOBE measurements in the 36–37 GHz band were performed on the Tier 1 commercial outdoor 5G mmWave gNodeB operating in the n260 Band (37–40 GHz) located at Table Mountain. Additional OOBE measurements were also conducted to observe the behavior of the OOBE below 36 GHz. The test cell site and measurement system used to perform these field measurements are described in detail. The stepped spectrum measurement used to perform these OOBE measurements is explained. Several spectrum captures are included to display both the in-band and out-of-band frequency characteristics of the mmWave signals. Determination of EIRP and a method to approximate the inferred TRP are included. ITS OOBE measurement results are compared to ITU Resolution 243 specifications.

The average EIRP integrated channel powers for both of the channels centered at 37.05 and 37.2 GHz *are not below* the ITU Resolution 243 unwanted emission mean power limit of −23 dBW/GHz or the recommended limit of −30 dBW/GHz. The inferred TRP integrated channel powers for both of the channels centered at 37.05 and 37.2 GHz *are below* the ITU Resolution 243 unwanted emission mean power limit of −23 dBW/GHz and the recommended limit of −30 dBW/GHz.

The motivation for accurate measurement results influenced the selection and development of the ITS measurement system and methods used in performing these OOBE measurements. Optimal measurement system specifications such as NF and measurement methods were explained and compared to less optimal measurement system specifications and measurement methods.

All measurements in this study were performed with the mmWave gNodeB operating in a single carrier 100 MHz mode with a single UE. Future work is planned for measurements including carrier aggregation of four 100 MHz carriers, multiple UE scenarios, and also with the mmWave gNodeB operating in a test mode (where no UEs are used) using a 3GPP test model. OOBE measurements with the mmWave gNodeB operating in a test mode are intended to show whether or not the OOBE are different than when the mmWave gNodeB is operating in a single carrier 100 MHz mode with a single UE.

14. Acknowledgments

This work was sponsored by the Office of Spectrum Management, National Telecommunications and Information Administration, U.S. Department of Commerce.

The authors would like to specifically thank the following individuals and organizations for their efforts in helping complete this work. Ric Freeman and Mike Chang were instrumental in helping set up the mobile antenna tower and rotator. Additionally, Mike Chang facilitated the process to obtain the required frequency licensing and coordination for operation of the test cell site at Table Mountain. Jason Parks designed, procured the necessary equipment for, installed, and tested the critical fiber link from Building I10C to Building T2 on Table Mountain. Greg Rice and Robert Booth set up, configured, and optimized the complex networking between the cellular system core network at the DoC Boulder Laboratories and the eNodeB/mmWave gNodeB at Building T2. Rob Grosso installed the iPerf server and client and provided expertise in running iPerf during the testing effort. Ashok Misra assisted in the acceptance testing of the mmWave gNodeB and provided great insight into the 5G signal configuration and parameters. Naser Areqat verified the correct profile was assigned to the SIM card used in the UE to allow it to attach to the mmWave gNodeB at Building T2. Tremendous support was given by the employees of our commercial cellular system equipment manufacturer who patiently configured and optimized the mmWave gNodeB during the acceptance testing, often working after midnight to accommodate the initial LTE frequency licensing constraints. In addition, our commercial cellular system equipment manufacturer conveyed valuable information concerning the 5G mmWave signal configuration and supplied enlightening operational antenna beamset diagrams. Shariq Ashfaq provided contacts and arranged initial meetings with DISH Wireless to coordinate spectrum usage of LTE Band 66. Hemant Mehta, Abid Khan, and Alison Minea from DISH coordinated the spectrum usage and authorized DISH approval for ITS to use Band 66 at Table Mountain. Daniel Krisak at DISH monitored and verified that ITS's transmissions in Band 66 did not negatively impact DISH's network. Brian Nelson of OSM provided support in completion of the OOBE field measurements at Table Mountain. Without the assistance of these individuals and organizations, this work would not have been possible.

15. References

[1] Federal Communications Commission, "In the Matter of Lower 37 GHz Band, Use of Spectrum Bands Above 24 GHz for Mobile Radio Services, Report and Order, Sixth Report and Order, and Further Notice of Proposed Rulemaking," *Report and Order*, *FNPRM*, 40 FCC Rcd 3413 (2025), accessed December 16, 2025. https://www.fcc.gov/document/fcc-clears-way-wireless-innovation-lower-37-ghz-band-0

[2] International Telecommunication Union-Radiocommunication Sector (ITU-R), "Resolution 243 (WRC-19) Terrestrial component of International Mobile Telecommunications in the frequency bands 37–43.5 GHz and 47.2–48.2 GHz," in *World Radiocommunication Conference 2019 (WRC-19): Final Acts* (Geneva, Switzerland: ITU, 2020), 355–356. https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.14-2019-PDF-E.pdf

[3] "Welcome to the Table Mountain Field Site and Radio Quiet Zone," Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U.S. Department of Commerce. https://its.ntia.gov/research-topics/table-mountain/tm-home.aspx

[4] "Communications Research and Innovation Network," Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U.S. Department of Commerce. https://its.ntia.gov/research/rat/communications-research-and-innovation-network/

[5] 3rd Generation Partnership Project, Technical Specification Group Service and System Aspects, *System architecture for the 5G System* (5GS), Stage 2 (Release 15), 3GPP TS 23.501 V15.13.0 (2022-03), 3GPP, Sophia Antipolis, France. https://www.3gpp.org/ftp/Specs/archive/23_series/23.501

[6] Sunsight Instruments MW08 Microwave Path Alignment Kit, Sunsight Instruments, LLC, accessed March 24, 2026. https://www.sunsight.com/download-datasheets/

[7] E.B. Larsen, R.L. Ehret, D.G. Camell, and G.H. Koepke, "Calibration of antenna factor at a ground screen field site using an automatic network analyzer," in *Proc. of the 1989 IEEE National Symposium on EMC*, (Denver, CO, May 1989), pp. 19–24. https://doi.org/10.1109/NSEMC.1989.37143

[8] Jeffery A. Wepman et al., "Outdoor Propagation Measurements in the 37–40 GHz Band in Boulder, Colorado," Technical Report NTIA TR-22-561, U.S. Department of Commerce, National Telecommunications and Information Administration, Institute for Telecommunication Sciences, August 2022. https://doi.org/10.70220/tr6xsd1g

[9] D. Camell, R. T. Johnk, D. Novotny, and C. Grosvenor, "Free-space antenna factors through the use of time-domain signal processing," in *Proc. of the 2007 IEEE International Symposium on Electromagnetic Compatibility* (Honolulu, HI, July 2007), pp. 1–5. https://doi.org/10.1109/ISEMC.2007.105

[10] Keysight Technologies, "Noise figure measurement accuracy: the Y-factor method," Application Note 5952-3706E, Jan. 25, 2021. https://www.keysight.com/us/en/assets/7018-06829/application-notes/5952-3706.pdf

[11] Jeffery A. Wepman and Geoffrey A. Sanders, "Wideband Man-Made Radio Noise Measurements in the VHF and Low UHF Bands," Technical Report NTIA TR-11-478, U.S. Department of Commerce, National Telecommunications and Information Administration, Institute for Telecommunication Sciences, July 2011. https://doi.org/10.70220/wqqjp3tf

[12] Keysight Technologies N9042B UXA X-Series Signal Analyzer, Multi-touch, Data Sheet, Keysight Technologies, Inc., June 24, 2025, 3121-1037, accessed April 22, 2026. https://www.keysight.com/us/en/assets/3121-1037/data-sheets/N9042B-UXA-X-Series-Signal-Analyzer-Multi-Touch.pdf

[13] International Telecommunication Union, Recommendation ITU-R P.525-4 (08/2019), *Calculation of free-space attenuation*, ITU, Geneva, Switzerland. https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.525-4-201908-S!!PDF-E.pdf

[14] Federal Communications Commission, Office of Engineering and Technology, Laboratory Division, "Basic Certification Requirements and Measurement Procedures for Upper Microwave Flexible Use Service (UMFUS) Devices," KDB 842590 D01 Upper Microwave Flexible Use Service v01r03, March 6, 2025. http://hctinsight.com/webzine/webzine/202504/file/fcc/fcc3.pdf

[15] 3rd Generation Partnership Project, Technical Specification Group Radio Access Network, NR, Base Station (BS) conformance testing, Part 2: *Radiated conformance testing (Release 19)*, 3GPP TS 38.141-2 V19.3.0 (2025-12), 3GPP, Sophia Antipolis, France. https://www.3gpp.org/ftp/Specs/archive/38_series/38.141-2

[16] CTIA Certification LLC, CTIA 01.90 Informative Reference Material, "Test plan for wireless device over-the-air performance," Version 6.0.2, April 2025. https://ctiacertification.org/wp-content/uploads/2021/02/CTIA-01.90-Informative-Reference-Material-V6_0_2.pdf

[17] Somayeh Mohammady, John Dooley, Ronan Farrell and Nasri Sulaiman, "Depiction of Peak to Average Power Ratio Reduction Scheme and potentials for 5G," *2018 IEEE International RF and Microwave Conference (RFM)*, Penang, Malaysia, 2018, pp. 286–290. https://doi.org/10.1109/RFM.2018.8846484

REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED START DATE	3. DATES COVERED END DATE
June 2026	Technical Report	March 2025	May 2026

4. TITLE AND SUBTITLE
Measured Out-of-Band Emissions in the 36–37 GHz Band from an n260 (37–40 GHz) Millimeter-Wave 5G Base Station

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER	5e. TASK NUMBER	5f. WORK UNIT NUMBER
6505 001 200		NTIA-ITS.SID

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8. PERFORMING ORGANIZATION REPORT NUMBER
NTIA TR-26-582

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Telecommunications and Information Administration
Office of Spectrum Management
Herbert C. Hoover Building
1401 Constitution Ave., N.W.
Washington, D.C. 20230

10. SPONSOR/MONITOR'S ACRONYM(S)
NTIA/OSM

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

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Out-of-band emissions (OOBE) measurements in the 36–37 GHz band were performed on a commercially available outdoor 5G millimeter-wave (mmWave) gNodeB operating in the n260 band (37–40 GHz). The 5G mmWave gNodeB is part of the Institute for Telecommunication Sciences (ITS) 5G mmWave test cell site located at the U.S. Department of Commerce Table Mountain Field Site and Radio Quiet Zone near Boulder, Colorado. The test cell site and measurement system used to perform these field measurements are described. Several spectrum captures are included to display both the in-band and out-of-band frequency characteristics of the mmWave signals. Determination of effective isotropic radiated power and a method to approximate the inferred total radiated power are included. These are used to facilitate the comparison of ITS OOBE measurement results to the limits set by the International Telecommunication Union Resolution 243 World Radiocommunication Conference 2019 specifications.

15. SUBJECT TERMS
36–37 GHz, 37–40 GHz, 5G, emissions measurements, gNodeB, International Telecommunication Union Resolution 243, millimeter wave, n260 band, out-of-band emissions, OOBE, total radiated power, TRP

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	C. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
Unclassified	Unclassified	Unclassified	UU	55

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