

American National Standard Methods of Measurement of the Electromagnetic and Operational Compatibility of Unlicensed Personal Communications Services (UPCS) Devices

C63[®]

Accredited Standards Committee C63[®] — Electromagnetic Compatibility

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American National Standards Institute

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American National Standard Methods of Measurement of the Electromagnetic and Operational Compatibility of Unlicensed Personal Communications Services (UPCS) Devices

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Secretariat

Institute of Electrical and Electronics Engineers, Inc.

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Abstract: Specific test procedures for verifying the compliance of unlicensed personal communications services (UPCS) devices (including wideband voice and data devices) are established including applicable regulatory requirements regarding radio-frequency emission levels and spectrum access procedures.

Keywords: ANSI C63.17, etiquette, personal communications, RF emissions, spectrum access, unlicensed devices, UPCS, wideband

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Introduction

This introduction is not part of ANSI C63.17-2013, American National Standard Methods of Measurement of the Electromagnetic and Operational Compatibility of Unlicensed Personal Communications Services (UPCS) Devices.

In November 1993, the Federal Communications Commission (FCC) invited ANSI C63 “to consider development of standard measurement procedures to support” proposed new provisions to Part 15 of Volume 47 of the Code of Federal Regulations (47CFR15) for unlicensed personal communications services (UPCS) devices.^a At its December 1993 meeting, ANSI C63 established a subcommittee (SC 7) to attempt to develop such standards in cooperation with representatives of the Wireless Information Networks Forum (WINForum) and other interested parties. The standard ANSI C63.17-1998 was the result of the efforts of SC 7.

In the Fall of 2004, the FCC revised provisions of 47CFR15 governing the 1920 MHz to 1930 MHz UPCS band. A working group was formed under the aegis of SC 7 to rewrite ANSI C63.17-1998 to reflect the changes in 47CFR15. This revised standard is, again, the result of the efforts of SC 7.

In July of 2012, the FCC released revised provisions of 47CFR15 governing the 1920 MHz to 1930 MHz UPCS band. These revisions facilitate the implementation of improved services utilizing this band. A working group was again formed under the aegis of SC 7 to revise ANSI C63.17-2006 to reflect the changes in 47CFR15. This revised standard is also the result of the efforts of SC 7.

^a Information on references can be found in Clause 2.

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1. Overview

1.1 Scope

This standard sets forth uniform methods of measurement of the electromagnetic and operational compatibility of *unlicensed personal communications services* (UPCS) devices. This standard does not cover licensed *personal communications services* (PCS) devices. The recommended methods are applicable to the radio transmitter and monitoring devices contained in the UPCS device. These methods apply to the measurement of individual UPCS devices. Additional methods may be added to this standard to fulfill future requirements.

In addition to the measurements specified herein, UPCS devices may also be required to be tested in accordance with other standards. Examples are listed in Annex A.

1.2 Applications

The procedures given herein may be used to test UPCS devices permitted under 47CFR15, Subpart D.¹ The emissions and operational characteristics of UPCS devices are the basic parameters affecting UPCS coexistence with other electronic devices and systems. In particular, compliance with this standard may be used to demonstrate electromagnetic compatibility with other UPCS systems and other systems operating in the same and adjacent frequency bands.

This standard describes preferred test methods, test facilities and, in some cases, alternative test methods and facilities. If these methods and facilities do not apply to the equipment under test (EUT), the manufacturer must explain why and must provide an alternative test procedure that has been approved by the applicable regulatory agency. If alternative test methods or facilities are employed, every effort should be made to establish correlation with the preferred ones.

Where the word *shall* is used in this document, it indicates something that is mandatory for compliance with this standard. The word *should* indicates something that is advisory only.

1.3 Roadmap to the document

The tests for UPCS devices fall into two categories. The first category includes the traditional set of radio-frequency (RF) measurements of radiated power, emission mask, power spectral density (PSD), etc. These tests are given in Clause 6 of this standard. The second category includes tests for the channel monitoring and access requirements unique to UPCS devices. These requirements are sometimes collectively referred to as the *spectrum etiquette*. The associated tests are described in Clause 7 and Clause 8 of this standard, and relate to 47CFR15.323. Section 15.323 of Title 47 of the Code of Federal Regulations requires that a UPCS device (the EUT) monitor the received RF power level on the intended transmit channel² before transmitting, and it also provides criteria that the monitored power level must satisfy to allow the EUT to transmit on that channel. The tests in Clause 7 and Clause 8 are designed to verify compliance with these requirements. Annex A provides a table showing the sections in 47CFR15 that correspond to the tests in this document.

To test for compliance with the monitoring and access requirements, it is necessary to subject the EUT to deliberate interference with controlled spectral and temporal characteristics on a selected channel or channels, and observe the reaction of the EUT. To restrict operation of the EUT to the selected channel(s), interference or administrative commands are used to block the other channels.

Clause 6, Clause 7, and Clause 8 give the fundamental tests. Clause 4 discusses test methodology for both radiated and conducted RF emission, monitoring, and access tests. Radiated tests measure field strength to determine the effective isotropic radiated power (EIRP), power density, and out-of-band emissions (Clause 6). For the monitoring and access tests of Clause 7 and Clause 8, a calibrated field strength is applied to the EUT if radiated measurements are used. If all EUT antennas are detachable, the tests of Clause 6, Clause 7, and Clause 8 shall be done on a conducted basis; that is, RF connections can be made between the EUT, its companion device, and the RF measuring instrument and interference generators via shielded coaxial cable. There must be adequate shielding around the EUT (and possibly the companion device) to prevent unintended RF coupling.

Clause 5 provides guidance on selection of measurement instrumentation, and Clause 9 summarizes the information that should be provided in the test report.

¹ Information on references can be found in Clause 2.

² Channel is used here to denote a time/spectrum window.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI C63.4, American National Standard for Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz.³

ANSI C63.14, American National Standard Dictionary of Electromagnetic Compatibility (EMC) including Electromagnetic Environmental Effects (E3).

ANSI C63.23, American National Standard Guide for Electromagnetic Compatibility Computations and Treatment of Measurement Uncertainty.

Code of Federal Regulations Title 47 Part 2 (47CFR2), Telecommunication—Frequency Allocations and Radio Treaty Matters: General Rules and Regulations.⁴

Code of Federal Regulations Title 47 Part 15 (47CFR15), Subpart D, Telecommunication—Radio Frequency Devices—Unlicensed Personal Communications Service Devices.

IEEE Std 149™-1979, IEEE Standard Test Procedures for Antennas.^{5, 6}

JCGM 100:2008, Evaluation of measurement data—Guide to the expression of uncertainty in measurement.⁷

NIS 81 (Edition 1, May 1994), The Treatment of Uncertainty in EMC Measurements.

NIS 3003 (Edition 8, May 1995), The Expression of Uncertainty and Confidence in Measurement for Calibrations.

NIST Technical Note 1297 (Sept. 1994), Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results.⁸

3. Definitions, symbols, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online*⁹ and ANSI C63.14 should be consulted for terms not defined in this subclause; unless otherwise noted herein, they apply throughout this document. Definitions in particular product standards or in applicable regulations take precedence.

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⁷ Joint Committee for Guides in Metrology (JCGM) document is available at <http://www.iso.org/sites/JCGM/GUM-JCGM100.htm>.

⁸ NIST publications are available from the National Institute of Standards and Technology (<http://www.nist.gov/>).

⁹ *IEEE Standards Dictionary Online* subscription is available at:
http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

activate: Apply power to the equipment under test (EUT); the EUT is running, but user-level communication is not occurring. For example, for a voice system after activation, the two ends of the link are synchronized, but no voice communication has begun. *See also:* **initiate**.

Butler matrix: A network of 3 dB hybrids that provides a passive combining/splitting function for coupling multiple radio-frequency (RF) inputs to multiple RF outputs.

channel: A repeated time and spectrum combination used for communications. In 47CFR15.323(c), the FCC uses the description a “combined time and spectrum window.”

NOTE—In this standard, *channel* and *access channel* have the same meaning.¹⁰

communications channel: A repeated time and frequency window whose primary purpose is the transmission of user-level communications. *See also:* **control and signaling channel**.

conducted emission and monitoring tests: Tests performed with radio-frequency (RF) signal sources (to test monitoring thresholds) and instrumentation (to measure emissions) connected directly to the antenna port on the equipment under test (EUT) transceiver through appropriate RF attenuation, if applicable, via shielded coaxial cable and passive combiner/splitter networks. *See also:* **radiated emission and monitoring tests**.

control and signaling channel: A repeated time and frequency window whose exclusive purpose is the transmission of information used by a system incorporating the equipment under test (EUT) to maintain timing synchronization or other information that does not require repeated and ongoing acknowledgement (e.g., a beacon used to broadcast a timing synchronization and identification signal). *See also:* **communications channel**.

different collocated antennas: Two or more antennas of substantially differing gains or efficiencies, with a mutual separation distance of 1 m or less, mounted on or within one housing, for the purpose of providing diversity against multipath fading.

digital modulation: The process by which the characteristics of a carrier wave are varied among a set of predetermined discrete values in accordance with a digital modulating function.

emission bandwidth (*B*): The bandwidth in hertz of the signal between two points, one below the carrier center frequency and one above the carrier center frequency, that are 26 dB down relative to the maximum level of the modulated carrier. It is based on the use of measurement instrumentation employing a peak detector function with an instrument resolution bandwidth (RBW) approximately equal to 1.0% of the measured emission bandwidth of the equipment under test (EUT) [see 47CFR15.303(c)].

frame jitter: Time-related, abrupt, spurious variations in the duration of the frame interval.

frame period: A set of consecutive timeslots in which the position of each timeslot can be identified by reference to a synchronizing source.

frequency administration commands: Means of control of the equipment under test (EUT) directly or through the companion device. This functionality is provided by the manufacturer to ease testability of the EUT. This functionality may include providing a control operator with external controls enabled to force the EUT to use only one or a subset of all the available carriers, and/or one or a subset of all of the available timeslots, and/or to disable diversity antenna selection. Functionality may be provided by the setting of unique values within nonvolatile memory in the EUT or companion device, or by other means not at variance with the requirements of 47CFR15.

¹⁰ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

identical collocated antennas: Two or more antennas of the same type, with substantially similar performance and with a mutual separation distance of 1 m or less, mounted on or within one housing, for the purpose of providing diversity against multipath fading.

initiate: Cause the equipment under test (EUT) to attempt to begin user-level communications, typically via the user interface, or in response to user-level data. For example, for a voice system, to initiate, press the TALK control to enable voice communications. *See also:* **activate**.

initiating device: An unlicensed personal communications service (UPCS) device that monitors both duplex channels of a duplex transmission pair in order to qualify both its own and a responding device's transmit channel for compliance with the spectral etiquette. This capability is used in accordance with 47CFR15.323(c)(10) to simplify the implementation of a UPCS system. *See also:* **responding device**.

least interfered channel (LIC): An interference avoidance mechanism that extends the listen before transmit (LBT) mechanism to monitor all potential channels, determining the LIC, before transmitting on that channel. Implementing the LIC algorithm removes the mandate to not transmit in a particular time/frequency combination if the observed other-user emissions in that time/frequency combination are above the threshold limit T_L for those systems offering 20 or more duplex communications channels.

listen before transmit (LBT): An interference avoidance mechanism that mandates monitoring of a selected channel to determine availability before transmission.

operational failure: The inability of an equipment under test (EUT) to perform a function that is required as a response to system conditions or to a manually or automatically initiated command.

peak transmit power (P_{EUT}): The peak power output observed over an interval of time equal to the transmission burst duration of the equipment under test (EUT) under all conditions of modulation.

power spectral density (PSD): The peak pulse power measured in a defined bandwidth.

radiated emission and monitoring tests: Tests performed with radio-frequency (RF) signal sources (to test monitoring thresholds) and instrumentation (to measure emissions) connected to test antennas. *See:* **conducted emission and monitoring tests**.

reaction time: The minimum duration of the interference present during the monitoring interval that must be detected by the equipment under test (EUT) so as to determine that the monitored time and spectrum window is occupied.

received signal strength indication (RSSI): A measure of the actual radio-frequency (RF) signal applied to the equipment under test (EUT) for a particular carrier/timeslot combination.

responding device: An unlicensed personal communications service (UPCS) device that does not monitor its own transmit channel, but rather operates in partnership with an initiating device, which monitors both duplex channels of a duplex transmission pair in order to qualify both its own and the responding device's transmit channel for compliance with the spectral etiquette. This capability is used in accordance with 47CFR15.323(c)(10) to simplify the implementation of a UPCS system. *See also:* **initiating device**.

RSSI monitoring means: Means of presenting the received signal strength indication (RSSI) measurements made on a particular timeslot and carrier by the equipment under test (EUT) to the test operator by the EUT directly or through the companion device. This functionality is provided by the manufacturer to ease testability of the EUT. Functionality may be enabled and controlled by the setting of unique values within nonvolatile memory in the EUT or companion device, or by other means not at variance with the requirements of 47CFR15.

spectrum window: An amount of spectrum bandwidth equal to the intended emission bandwidth in which operation is desired.

steady state: The mode of operation other than during a temporary or transient event such as stopping transmission on one timeslot/frequency allocation and starting transmissions on another timeslot/frequency allocation, a handover in response to channel conditions.

thermal noise power: The noise power in watts defined by the formula $N = kTB$, where N is the noise power in watts, k is Boltzmann's constant, T is the absolute temperature in degrees Kelvin (e.g., 295 K), and B is the emission bandwidth of the equipment under test (EUT) in hertz.

threshold limit (T_L): The level of other-user signal that constitutes the maximum threshold for an active channel for the equipment under test's (EUT's) listen before transmit (LBT) algorithm if the EUT system does not implement the *least interfered channel* (LIC) function in accordance with 47CFR15.323(c)(5), taking into account the transmission bandwidth and actual transmit power of the EUT.

time window: An interval of time in which transmission is desired.

unlicensed personal communications service (UPCS) device: Intentional radiators operating in the frequency band specified by the applicable regulating agency that provide a wide array of mobile and ancillary fixed communication services to individuals and businesses without requiring operational license from the regulatory agency.

3.2 Symbols

B_{limitL} : The measured emissions bandwidth must be greater than B_{limitL} [see 47CFR15.323(a)].

B_{limitU} : The measured emissions bandwidth must be less than B_{limitU} [see 47CFR15.323(a)].

D : The largest linear dimension of the body of the EUT.

E_{EUTmax} : The maximum field strength of radiated emissions at the angle and polarization of maximum antenna gain.

G : Antenna maximum gain above which maximum allowable transmit power is reduced [see 47CFR15.319(e)].

G_A : EUT antenna gain at the angle and polarization of maximum gain, expressed as decibels relative to isotropic antenna gain (dBi).

M_L : The maximum amount in decibels by which the limiting threshold may exceed thermal noise for an EUT transmitting the maximum allowed power.

P_{limit} : The peak transmit power that the EUT must not exceed, taking into account antenna gain (G_A) and emissions bandwidth.

P_{max} : The peak transmit power that the EUT must not exceed, if antenna gain is less than G , taking into account emissions bandwidth.

PSD_{EUT} : The EUT's maximum of peak transmit power measured in any 3 kHz bandwidth.

$\text{PSD}_{\text{limit}}$: The peak transmit power in any 3 kHz measurement bandwidth that the EUT must not exceed.

P_{Tref} : The power to be applied to a reference antenna input connector on a radiated test range, at a level necessary to achieve the desired signal level at the EUT.

U_M : Margin of 6 dB for uncertainty in the threshold measurements, incorporating the effects of EUT measurement noise and uncertainty.

3.3 Acronyms and abbreviations

B	emissions bandwidth
C	center frequency
CMOS	complementary metal-oxide semiconductor
CW	continuous wave
dBc	decibels relative to the total carrier power
dB _i	decibels referenced to isotropic antenna gain
dB _m	decibels referenced to one milliwatt
dB μ V/m	field strength in decibels referenced to one microvolt per meter
EIRP	effective isotropic radiated power
EUT	equipment under test
FDMA	frequency-division multiple access
g	antenna gain
JCGM	Joint Committee for Guides in Metrology
k	Boltzmann's constant
LBT	listen before transmit
LIC	least interfered channel
LVDS	low-voltage differential signaling
M_L	limiting interference threshold (decibels above thermal)
N	thermal noise
O	frequency offset
OATS	open-area test site
PCS	personal communications services
P_{EUT}	peak transmit power
ppm	parts per million
PSD	power spectral density
RBW	resolution bandwidth

RF	radio frequency
RSSI	received signal strength indication
TDD	time-division duplexing
TDMA	time-division multiple access
TEM	transverse electromagnetic
T_L	threshold limit
T_M	received signal level threshold
U_M	provision for measurement uncertainty and noise
UPCS	unlicensed personal communications services
VHDCI	very high density cable interconnect

4. Radiated and conducted emissions test methodology

To perform the RF emission tests in Clause 6 and the monitoring and access tests in Clause 7 and Clause 8, it is necessary to have controlled RF paths between the EUT and the measurement instrumentation, as well as between the EUT and the interference generators. If the EUT requires a companion device to operate, there must also be a controlled RF path between the EUT and its companion device.

These controlled RF paths may be realized either as “radiated” (through space) or “conducted” (over coaxial cable) paths. In the radiated case, the tests must be performed in a facility with controlled RF propagation characteristics, so that the path loss can be controlled by varying separation between transceiver and monitoring/source antennas. In the conducted case, the tests can be performed anywhere there is adequate shielding to prevent external interference from affecting the test results. Signals can be combined and distributed using passive networks (e.g., RF attenuators, Butler matrices,¹¹ directional couplers). Path loss can be controlled with RF attenuators.

This clause provides guidance on implementation of the conducted and radiated measurements of transmit power output and monitoring threshold. Supporting derivations are given in Annex B.

Conducted tests are preferred to radiated tests and should be used for tests not affected by antenna selectivity if the EUT antenna can be detached for testing purposes. If the EUT antenna or antennas are replaced by a direct connection, the connection should be made in an impedance-matched fashion so that matching losses relative to the antenna connection are less than 2 dB.

If the test methods are not given in this standard, the procedures recommended by ANSI C63.4 and other applicable standards shall be used.

The guidance of JCGM 100:2008 shall be used when evaluating the measurement uncertainty for tests performed to this standard.

¹¹ A Butler matrix is a network of 3 dB hybrids that provides a passive combining/splitting function for coupling multiple RF inputs to multiple RF outputs.

4.1 Test facilities and equipment

Tests should be performed at the manufacturer's recommended normal operating temperature and voltage.¹² Unless stated otherwise, the requirements of ANSI C63.4 apply to the test facilities, including the site design, dimensions, and validation. Portions of this standard place requirements on the test facilities, in addition to the general requirements of ANSI C63.4.

When shielding facilities (shielded room, semi-anechoic chamber, or anechoic chamber) are used for operational compatibility testing, the shielding effectiveness of the room shall be such as to ensure compliance with electromagnetic emission limits for the environment outside of the room and reduce the ambients penetrating into the room to levels at least 10 dB below the weakest measured signal.

When the free-space test environment is simulated, the reflections from the facility confines, as well as the reflections from any extraneous objects at the test site, must be reduced to levels at least 10 dB below the direct (free-space) signal.¹³

The diagram in Figure 1 lists the types of test facilities that may be used for measurements specified in this standard.

In all cases, the test facilities and equipment must be fit for the purpose of measuring the parameters and operations of the EUT according to the requirements of 47CFR15, and in accordance with good engineering practice.

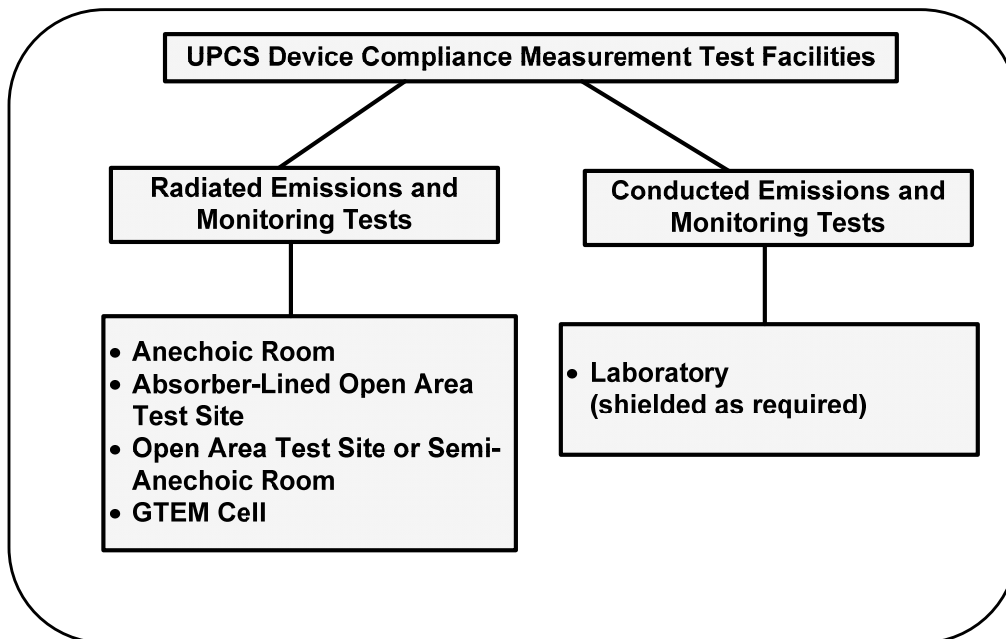


Figure 1—Test facilities that may be used

¹² Use ambient conditions unless otherwise specified as in Table 7. Nominal mains voltage of 115 V (ac) (or fresh battery pack as appropriate) may be used.

¹³ To check for reflections or other influence from nearby objects move the EUT one-quarter-wavelength relative to the structure, repositioning the measurement antenna or probe, so as to keep the same relative spacing between the EUT and measurement antenna or probe. Compare the results. The EUT may also be reoriented by 45° or 90° and measured.

The RF ambient and instrumentation noise floor shall be > 20 dB below the intended measurement limit.

If it is not practical to measure the reflection loss, then the two-wavelength spacing rule may be used. By this rule, all potentially reflective objects are kept greater than two wavelengths away from the EUT.

4.2 Test configurations and setup

Clause 6 provides detailed tests of parameters related to RF emissions, such as peak transmit power, emission bandwidth, and PSD. Those tests are similar to emission tests performed on most non-UPCS devices. Clause 7 and Clause 8 provide tests that verify compliance with the monitoring and access requirements that are unique to UPCS devices. These tests require observation of the electrical performance characteristics of the EUT in the presence of controlled interference of a specific frequency, power level, and modulation format. The monitoring and access tests have implications for the conducted and radiated test setups.

The *monitoring antenna* refers to the EUT antenna used to monitor the RF signal on the channel prior to transmission. In many cases, the monitoring antenna will be the same as the transmitting antenna. If it is not, then the monitoring and access tests are further complicated by the need to ensure that the monitoring antenna provides “coverage” that is at least equivalent to that which would be provided by the transmit antenna.

This standard identifies six test configurations. Each configuration is discussed in a separate subclause as shown in Table 1.

Table 1—Test specifications for different antenna configurations

Transmit/monitoring Antenna comparison and placement	Subclause	
	Conducted measurement based test (preferred)	Radiated measurement based test
Single or identical collocated	4.5	4.8
Different collocated	4.6	4.9
Arbitrarily placed	4.7	4.10

Independent of antenna type and placement, the measurement type (i.e., conducted or radiated) can be selected by the product manufacturer and specified in the compliance report. Conducted measurements are generally required for systems with detachable antennas for measurements where antenna frequency selectivity is not a factor.

Compliance measurements utilize standard electromagnetic compatibility (EMC) and antenna techniques for conducted power, radiated field, and EIRP measurements. The conducted test setup is based on power measurements at the EUT transmit, receive, and monitoring antenna terminals. The associated compliance limits for the UPCS products depend on the transmit antenna gain G_A . The value of G_A is declared by the manufacturer.

Since the transmitter and receiver radiated power parameters can be expressed in several different but equivalent ways, a number of alternative compliance test procedures can be used for radiated measurements. The general radiated test setup is based on free-space environment measurements as shown in Figure 2, where D is the largest dimension of the EUT (see Figure 3 for the general conducted test setup). The free-space test site is defined such that the reflections from any ground planes and other reflecting objects are at least 10 dB below the line-of-sight signal. The reference antenna is used to measure the EUT radiating power and to establish the monitoring threshold fields at the transmit and monitoring antennas. The associated compliance limits are based on the EIRP. The antenna gain and the EIRP evaluations should be performed as recommended in IEEE Std 149-1979.

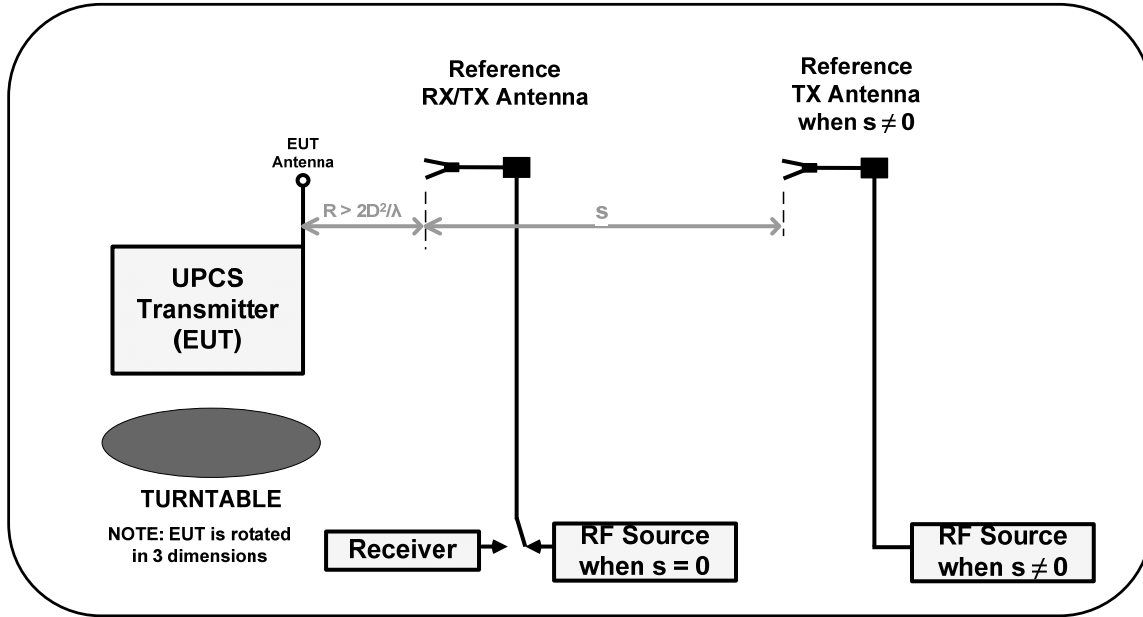


Figure 2—Radiated measurements in free-space environment

Equivalent radiated tests can be performed in facilities that do not provide for a free-space environment and/or measure radiated power [wideband transverse electromagnetic (TEM), etc.]. Instead of using the reference antenna, the necessary power levels are generated and/or measured by the test facility itself. If alternative measurements are used, the test results must be correlated with those obtained using antenna measurements in a free-space environment.

4.3 Transmitted power and monitoring threshold limits

The spectrum etiquette for UPCS systems requires that one or both ends of a linked pair monitor a channel for other users in proximity, prior to transmitting. The EUT, if it does not implement the LIC algorithm, or if it does not offer at least 20 duplex communications channels, must defer using the channel if the amount of signal detected from other devices using the channel is above a threshold. EUT systems that support 20 or more duplex communications channels and implement the LIC algorithm are permitted to exceed the threshold for signals detected from other users, in selecting a channel for transmissions; EUT systems that support a lesser number of channels or do not implement the LIC algorithm are required to defer transmissions unless other-user signal levels detected are below the limiting threshold. EUT transmit power is also limited, and the limiting threshold is adjusted to normalize the anticipated interference generated by an EUT in proportion to its transmit power.

4.3.1 Peak transmit power

P_{EUT} , the EUT transmit power at the antenna terminals, must be less than a maximum, as shown in Equation (1):

$$P_{EUT} \leq P_{\text{limit}} \text{ where } P_{\text{limit}} = \begin{cases} P_{\text{max}} - (G_A - g), & \text{when } G_A > g \\ P_{\text{max}}, & \text{when } G_A \leq g \end{cases} \quad (1)$$