2/3/2011

Federal Communications Commission
Office of Engineering and Technology
Laboratory Division Public Draft Review

Draft Laboratory Division Publication

Title: Conducted Emissions Testing of Transmitters with Multiple Outputs in the Same Band (*e.g.,* MIMO, Smart Antenna, etc)

Short Title: Multiple Transmitter Output

Reason: New Publication

Publication: 662911

Keyword/Subject: Measurement of Transmitters with Multiple Output, MIMO, Smart Antenna

First Category: Administrative Requirements

Second Category: Measurement procedure

Third Category:

Question: How are measurements made on devices that employ a single transmitter with multiple outputs in the same band?

Answer: The attached document, 662911 D01 Multiple Transmitter Output v01, provides guidance for measurements of conducted output emissions of devices that employ a single transmitter with multiple outputs in the same band. The guidance applies to devices that transmit on multiple antennas simultaneously in the same band through a coordinated process. Examples include, but are not limited to, devices employing beamforming or multiple-input and multiple-output (MIMO.) This guidance applies to both licensed and unlicensed devices wherever the FCC rules call for conducted output measurements. Guidance is provided for in-band, out-of-band, and spurious emission measurements.

Attachment List:
662911 D01 Multiple Transmitter Output v01

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Conducted Emissions Testing of Transmitters with Multiple Outputs in the Same Band (*e.g.*, MIMO, Smart Antenna, etc.)

This document provides guidance for measurements of conducted output emissions of devices that employ a single transmitter with multiple outputs in the same band. It applies to devices that transmit on multiple antennas simultaneously in the same band through a coordinated process. Examples include, but are not limited to, devices employing beamforming or multiple-input and multiple-output (MIMO.) This guidance applies to both licensed and unlicensed devices wherever the FCC rules call for conducted output measurements. Guidance is provided for in-band, out-of-band, and spurious emission measurements.

This guidance does not apply to the multiple transmitters included in a composite device, such as a device that combines an 802.11 modem with a cell phone in one enclosure with each driving its own antenna.

INTRODUCTION

This document addresses two issues associated with conducted testing of emissions from transmitters with multiple outputs in the same band.

(1) *Combining emissions*. The FCC's emission limits apply to the total of emissions from all outputs of the transmitter. Thus, emissions from the transmitter outputs must be combined or summed before comparing measured emissions to the emission limit.

(2) *Accounting for array gain*. Correlation between signals transmitted from different antennas can lead to array gain, which increases the directional gain of the device and leads to higher radiated levels in some directions. The contribution of array gain to the directional gain of the transmitter must be considered in rule parts where conducted in-band emission limits vary with directional gain, or in situations in which conducted measurements are combined with directional antenna gain to determine compliance with in-band radiated limits.

These issues are unique to conducted emissions measurements. Radiated measurements automatically combine the power emitted from multiple outputs and include the effects of directional gain if the measurements are performed in the direction of maximum response of the transmitter.

Accordingly, this document provides guidance on the following considerations related to conducted emissions testing:

(1) How to combine emissions from multiple outputs of a transmitter;

(2) How to include array gain in directional gain computations for rules that depend on directional gain of the transmitter.

This document deals only with methodologies for combining emissions from multiple outputs of a transmitter, and for computing the increase in directional gain that can result from transmitting correlated signals on multiple outputs of a transmitter. This guidance makes no change regarding other aspects of measurements and compliance, such as the type of power or power spectral density measurement to be made (*e.g.*, peak or average) or the methods for making those measurements (*e.g.*, spectrum analyzer setup parameters).

AVAILABLE METHODOLOGIES FOR COMBINING EMISSIONS FROM MULTIPLE OUTPUTS OF A TRANSMITTER

In most rule parts where conducted output emission limits are specified, the limits are defined in terms of the total power, or the power within a specified measurement bandwidth. These power levels are intended to include the total power from all of the outputs of the transmitter.

Two techniques have commonly been used to combine emissions from multiple outputs in order to characterize the total emission level: (1) measure and sum; and, (2) a combiner.

In the measure and sum approach, the conducted emission level (*e.g.,* transmit power or power in specified bandwidth) is measured at each antenna port. The measured results at the various antenna ports are then summed mathematically to determine the total emission level from the device. Summing is performed in linear power units (*e.g.,* mW—not dBm).

In some cases, an electrical combiner has been used to combine the emissions from the various outputs before measurement. In such cases, a 0-degree combiner is used and adjustments must be made for insertion loss of the combiner. After correction for insertion loss, measurements made using a combiner will correctly indicate the transmitter's total output power in the measurement band only if transmitted signals are uncorrelated at zero time-delay. Otherwise, the measurement result may be too high if the transmitted signals are positively correlated or too low if the transmitted signals are negatively correlated. The positive-correlation case, where the measured emission level is too high, could lead to rejection of a device that actually complies with the limits. The negative-correlation case, where the measured emission level is too low, could lead to approval of a device that does not actually comply with the limits.

Because of the possibility of incorrect measurements resulting from correlation between signals on the various the transmitter outputs, use of a combiner is no longer permitted for any conducted testing of emissions--either in-band or out-of-band and spurious.

The next section of this document provides guidance on the application of the measure-and-sum technique and another simpler approach for addressing the need to combine emissions from multiple outputs before comparison to the emission limit.

GUIDANCE FOR COMBINING EMISSIONS FROM MULTIPLE OUTPUTS OF A TRANSMITTER

Acceptable methodologies for combining emissions from multiple outputs of a transmitter depend on the type of emission measurement being made. Three types of emission measurements are considered: in-band power measurements; in-band power spectral density measurements; and out-of-band and spurious emissions measurements.

In-Band Power Measurements

The measure-and-sum technique should be used for measuring in-band transmit power of a device. A combiner should not be used.

In-Band Power Spectral Density (PSD) Measurements

The guidance shown in item (1) in this section represents a clarification of previous guidance provided by the FCC. That in item (2) is an alternative measurement method that was not included in previous guidance.

When performing PSD measurements within the band of operation of a transmitter, either of two techniques may be used to combine the emissions from multiple outputs prior to comparing to the emission limit. The first is the most accurate method. The second technique is offered as a simpler alternative, but it may lead to an overestimate of the total PSD when emission levels differ between outputs; consequently, if measurements performed using method (2) exceed the emission limit, the test lab may wish to retest using method (1) before declaring that the device fails the emission limit. A combiner should not be used.

(1) *Measure and sum the PSDs across the outputs*. With this technique, PSD is measured at each output of the device. The individual PSDs are then summed mathematically in linear power units. Unlike in-band power measurements, in which the sum involves a single measured value (output power) from each output, summing of PSDs involves summing entire spectra across corresponding frequency bins on the various outputs (*i.e.*, for a device with N transmitter outputs, if the PSD measurements of the individual outputs are all performed with the same span and number of points, the PSD value (in watts or milliwatts) in the first spectral bin of output 1 is summed with that in the first spectral bin of output 2 and that from the first spectral bin of output 3, and so on up to the N^{th} output to obtain the PSD value for the first frequency bin of the summed spectrum. The total PSD value for each of the other frequency bins is performed in the same way). This will likely require transferring the measured spectra to a computer, where the bin-by-bin summing can be performed.

(2) *Measure and add 10 log(N) dB*, where N is the number of outputs. With this technique, PSD is measured at each output of the device, but rather than summing the

PSDs across the outputs, the quantity *10 log(N)* dB is added to each PSD and the result is compared to the emission limit. The addition of *10 log(N)* dB serves to apportion the emission limit among the N outputs so that each output is permitted to contribute no more than $1/N^{th}$ of the total PSD permitted in the specified measurement bandwidth by the rules. (Note that the *10 log(N)* term in this calculation is not related to that used in array gain calculations, to be discussed later in this document.)

With either method, existing rules and guidance should be applied in performing the measurements on the individual outputs and in determining the maximum permitted PSD for the device.

Out-of-Band and Spurious Emission Measurements

The guidance in this section represents a change from previous guidance provided by the FCC. Use of a combiner is no longer permitted. Emissions measured on individual channels must either be summed across the outputs or adjusted by 10 log(N) before comparison to the emission limit. New guidance is also provided for cases involving relative emission limits.

When performing measurements outside of the band of operation of a transmitter (*i.e.*, out-of-band and spurious emissions), either of two techniques may be used to combine the emissions from multiple outputs prior to comparing to the emission limit. The first is the most accurate method. The second is offered as a potentially simpler alternative, but may lead to an overestimate the total PSD when emission levels differ between outputs; consequently, if measurements performed using method (2) exceed the emission limit, the test lab may wish to retest using method (1) before declaring that the device fails the emission limit.

(1) *Measure and sum PSDs across the outputs* (as described in the preceding section).

(2) *Measure and add 10 log(N) dB* (as described in the preceding section).

When testing out-of-band and spurious emissions against relative emission limits, tests may be performed on each output individually without summing or adding *10 log(N)* if the measurements are made relative to the in-band emissions on the individual outputs. For example, if a rule states that out-of-band emissions in a 100 kHz bandwidth must be at least 20dB below the highest power 100 kHz in-band, compliance may be established by confirming that the maximum total out-of-band emission is at least 20 dB below the maximum in-band PSD, as determined by the “measure and sum PSDs” technique in both instances; alternatively, compliance may be demonstrated by confirming that the maximum out-of-band emission on each individual output is at least 20 dB below the maximum in-band PSD on that output. Similarly, if a rule states that out-of-band emissions in a 1MHz bandwidth must be at least *X dB* below the transmit power (where *X* does not vary with transmit power), compliance may be established by confirming that the maximum total out-of-band emission, as determined by the “measure and sum PSDs” technique, is at least *X dB* below the total transmit power. as determined by the “measure and sum” technique; alternatively, compliance may be demonstrated by confirming that the maximum out-of-band emission on each individual output is at least *X dB* below the maximum transmit power on that output.

Emission limits specified as *X + 10 log(P) dB* below the transmit power (where *P* is the transmit power) are absolute limits and are not considered "relative limits" for purposes of this guidance. Out-of-band and spurious emissions must be tested against absolute limits using techniques (1), (2), or (3) described above.

GUIDANCE ON DIRECTIONAL GAIN CALCULATONS

The guidance in this section clarifies previous guidance and identifies an additional category of devices that may be considered to have uncorrelated output transmissions relative to previous guidance provided by the FCC.

Some rule parts define a limit on output power or power spectral density that is a function of the directional gain of the antenna system. There may also be cases in which conducted measurements are combined with directional antenna gain to determine compliance with in-band radiated limits. In such cases, the effect of array gain must be included in the calculation of overall directional antenna gain for devices that transmit on multiple outputs simultaneously in the same band.

Array gain results when the signals transmitted on different antennas are correlated when viewed from a specific direction. In most cases, beamforming systems attempt to achieve 100 percent correlation between the transmitted signals when viewed from the intended beam direction, though actual correlation may be slightly lower. A transmitter that transmits correlated signals from its multiple antennas has the potential to create array gain even when that is not the intent.

For simplicity, the guidance presented here categorizes transmissions as *correlated* (*i.e.*, correlation exists between the signals on at least two antennas) or *completely uncorrelated*. Unless the transmitted signals are categorized as completely uncorrelated based on the guidance provided below, the signals must be considered correlated for the purposes of computing directional gain. In the case of correlated signals, array gain will be computed based on 100 percent correlation even if the actual correlation is lower.

Categorization as Correlated or Completely Uncorrelated

For the purposes of this guidance, transmitter output signals are considered *correlated* if any of the following are true:

- The same digital data are transmitted from two or more antennas in a given symbol period, even with different coding or phase shifts; or,
- Correlation between two transmitted signals exists at any frequency and time delay; or,
- Multiple transmitter outputs serve to focus energy in a given direction or to a given receiver; or,
- The operating mode combines correlated techniques with uncorrelated techniques.

Otherwise, the output signals are considered *completely uncorrelated*.

Correlated signals include, but are not limited to, signals transmitted in any of the following modes:

- *Any transmit beamforming mode,* whether fixed or adaptive (*e.g.*, phased array modes, closed loop MIMO modes, Transmitter Adaptive Antenna modes, Maximum Ratio Transmission (MRT) modes, and Statistical Eigen Beamforming (EBF) modes).
- *Cyclic Delay Diversity (CDD) modes* (e.g., legacy modes in 802.11n devices). In CDD modes, the same digital data is carried by each transmit antenna, but with different cyclic delays. The signals are highly correlated at any one frequency, though not necessarily at zero time delay. In particular, correlations tend to be high over the bandwidths specified for in-band PSD measurements in FCC rule parts that require reductions in PSD when directional gain exceeds a threshold.

Completely uncorrelated signals include those transmitted in the following modes, if they are not combined with any correlated modes, such as beamforming:

- Space Time Block Codes (STBC) or Space Time Codes (STC) for which different digital data is carried by each transmit antenna during any symbol period (*e.g.*, WiMAX Matrix A [Alamouti coding]).
- Spatial Multiplexing MIMO (SM-MIMO), for which independent data streams are sent to each transmit antenna (*e.g.*, WiMAX Matrix B. WiMAX Matrix C, which adds diversity, also produces uncorrelated transmit signals).

[Note that under previous guidelines, only SM-MIMO signals could be considered uncorrelated for purposes of directional gain computation.]

The FCC Laboratory may consider adjustments to this guidance as new modes of operation are brought to its attention.

Directional Gain Calculations

In the commonly occurring case of N transmit antennas, each with the same directional gain G_{ANT} dBi, being driven by N transmitter outputs of equal power, directional gain is to be computed as follows:

- If any transmit signals are ***correlated*** with each other,
  Directional gain = G_{ANT} + 10 log(N) dBi
- If all transmit signals are ***completely uncorrelated*** with each other,
  Directional gain = G_{ANT}

In the following special cases, directional gain should be computed as specified below:

- *Sectorized antenna systems*. In sectorized antenna systems in which each antenna is used to transmit different data in a different direction from the other antennas, directional gain is equal to the gain of an individual sector antenna.
- *Cross-polarized antennas with N = 2*. In the case of a transmitter with only two outputs driving antennas that are cross-polarized (*e.g.*, vertical and horizontal or left-circular and right-circular), directional gain is the gain of an individual antenna.
- *Unequal antenna gains, with equal transmit powers*. For antenna gains given by G_1, G_2, …, G_N dBi

◊ If transmit signals are *correlated*, then

Directional gain = 10 log[$(10^{G1/20} + 10^{G2/20} + \ldots + 10^{GN/20})^2$ /N] dBi [Note the "20"s in the denominator of each exponent and the square of the sum of terms; the object is to combine the signal levels coherently.]

◊ If all transmit signals are *completely uncorrelated*, then

Directional gain = 10 log[$(10^{G1/10} + 10^{G2/10} + \ldots + 10^{GN/10})$/N] dBi