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Range Extension for IEEE® 802.15.4 and ZigBee™ Applications

1 Introduction

The Freescale series of ZigBee™ transceivers, which includes the MC1319x, MC1320x, and MC1321x, are IEEE® 802.15.4 Standard compliant, 2.4 GHz Industrial, Scientific, and Medical (ISM) band transceivers. Typical intended applications include, but are not limited to the following:

- Remote control and wire replacement in industrial systems such as wireless sensor networks
- Factory automation and motor control
- Energy Management (lighting, HVAC, etc.)
- Asset tracking and monitoring
- Home automation and control (lighting, thermostats, etc.)
- Human interface devices (keyboard, mice, etc.)
- Remote entertainment control
- Wireless toys

To extend the functionality of these devices into other application spaces, it is possible to trade low power consumption for range by adding an external Power

Contents

Amplifier (PA) and/or a Low Noise Amplifier (LNA). This note provides general guidance on using these external components. A major consideration in the selection of a PA and/or LNA are the limits imposed by the following standards:

- IEEE 802.15.4
- FCC 15.247
- RSS-210
- ETSI EN 300 328
- ARIB STD-T66

Other local regulations and limits may apply. Approval for an end product solution under these standards is done on a case by case basis. Freescale recommends that a competent approval body and/or a consultant in the field be consulted as early as possible in the design process. Additionally, Freescale cannot by held liable for the use of the information contained herein, which is meant to provide general guidance only.

All calculations contained in this note are based upon a nominal 0dBm output power from the transceiver. The detailed performance of the transceiver can be found in the respective device data sheet and/or reference manual.

2 General Requirements

The PA and LNA general requirements described in this note are limited to applications in the 2.4GHz ISM band.

2.1 IEEE 802.15.4 Parameters

The following parameters defined in the IEEE 802.15.4 standard are met or exceeded by the performance of the Freescale transceivers and should not be degraded by the addition of a PA in the transmit path:

- Tx maximum output power is -3dBm at the lower limit and are not specified for the upper limit. The regulatory bodies do specify an upper limit to the maximum output power, which will be covered in a later section.
- Carrier accuracy and modulation accuracy are not to exceed +/-40ppm.
- EVM cannot exceed 35%.
- Tx spectral density has to be less than -20dBc relative to carrier and less than -30dBm absolute power, both at +/-3.5MHz offset from highest average spectral power measured within +/-1MHz of carrier. Relative and absolute spectral powers are measured with a 100kHz bandwidth.

Tx power control range and Tx power step size are not explicitly set by the 802.15.4 standard. However, Section 6.7.6 states, “Devices should transmit lower power when possible in order to reduce interference to other devices and systems”.

For any design that uses an external LNA, ensure that the design meets the requirements as described in the following sections of the IEEE 802.15.4 Standard:

- Section 6.5.3.4 (Jamming Resistance)
- Section 6.7.6 (Receiver Maximum Input Level)

2.2 Regulatory Standards (Transmitter Output Power)

The maximum allowed output power of the transmitter with the external PA is defined by the regulatory standards and is summarized in Table 1.

Table 1. Max Transmitter Output Power as Defined by Regulatory Standards

Geographical Region	Radiated Power (EIRP)	Conducted Power	Max Allowed Antenna Gain	Standard
-United States / Canada	-	1 W 30 dBm	6 dBi	FCC 15.247 RSS-210
Europe	100 mW (20 dBm)	-	0 dBi (Peak gain above 0 dBi reduces the allowable TX power by the same amount.)	EN 300 328
Japan	-	10 mW/MHz 10 dBm/MHz	2.14dBi for conducted test	ARIB STD-T66

In Figure 1, the output power limits for conducted measurements, as listed in Table 1, are superimposed on a measured 2480MHz modulated carrier with no external PA.

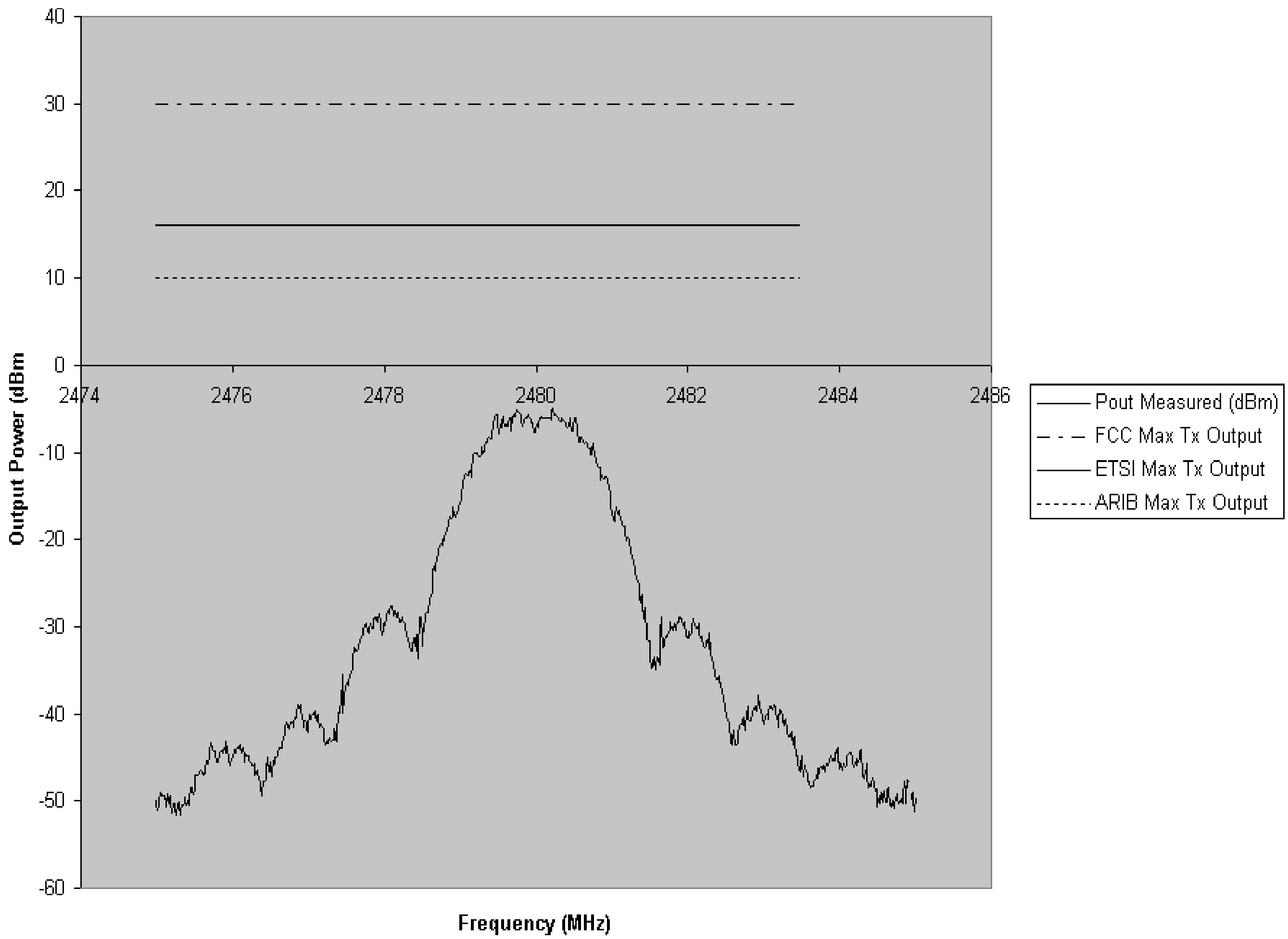

Figure 1. Tx Output Power Limits on Modulated Spectrum (MHz)

2.3 Regulatory Standards (Spurious Emissions)

The regulatory standards set limits on the spurious emissions and are summarized in Table 2. FCC and some ETSI standards tests are radiated measurements, which are affected by the antenna gain at the frequency of interest. Table 2 also lists FCC limits for a 100 percent duty cycle only. The FCC does allow for a reduction in duty cycles to a minimum of 10%, which translates to an increase on the spurious emissions limits.

NOTE

ETSI and ARIB do not allow any relaxation of limits for duty cycle.

Table 2. Max Transmitter Spurious Emissions as Defined by Regulatory Standards

Geographical Region	Radiated Power (EIRP)	Conducted Power	Relevant Frequency Bands	Standard
United States/Canada	-41.2 dBm/MHz	-	Restricted Bands: 2310 – 2390 MHz 2483.5 – 2500 MHz 4.5 – 5.15 GHz 7.25 – 7.75 GHz 10.6 – 12.7 GHz 14.47 – 14.5 GHz 17.7 – 21.4 GHz 22.01 – 23.12 GHz	FCC 15.247 RSS-210
	-	-20 dBc	All frequencies not listed in above cells.	-
Europe	-36 dBm/MHz	-	30 MHz – 1 GHz	EN 300 328
	-30 dBm/MHz	-	1 GHz – 12.75 GHz	-
	-47 dBm/MHz	-	Restricted Bands: 1.8 – 1.9 GHz 5.15 GHz – 5.3 GHz	-
Japan	-	25 µW/MHz -16.02 dBm/MHz	2387 – 2400 MHz 2483.5 – 2496.5 MHz	ARIB STD-T66
	-	2.5 µW/MHz -26.02 dBm/MHz	10 – 2387 MHz 2496.5 – 8000 MHz	-

The strictest limitations to using an external PA are those imposed by the FCC on the frequencies directly adjacent to the upper and lower edges of the 2.4 GHz ISM band. As shown in Figure 2, the channel that most closely falls into an FCC restricted band is the upper channel at 2480MHz. There is more margin for the lower channel at 2405MHz.

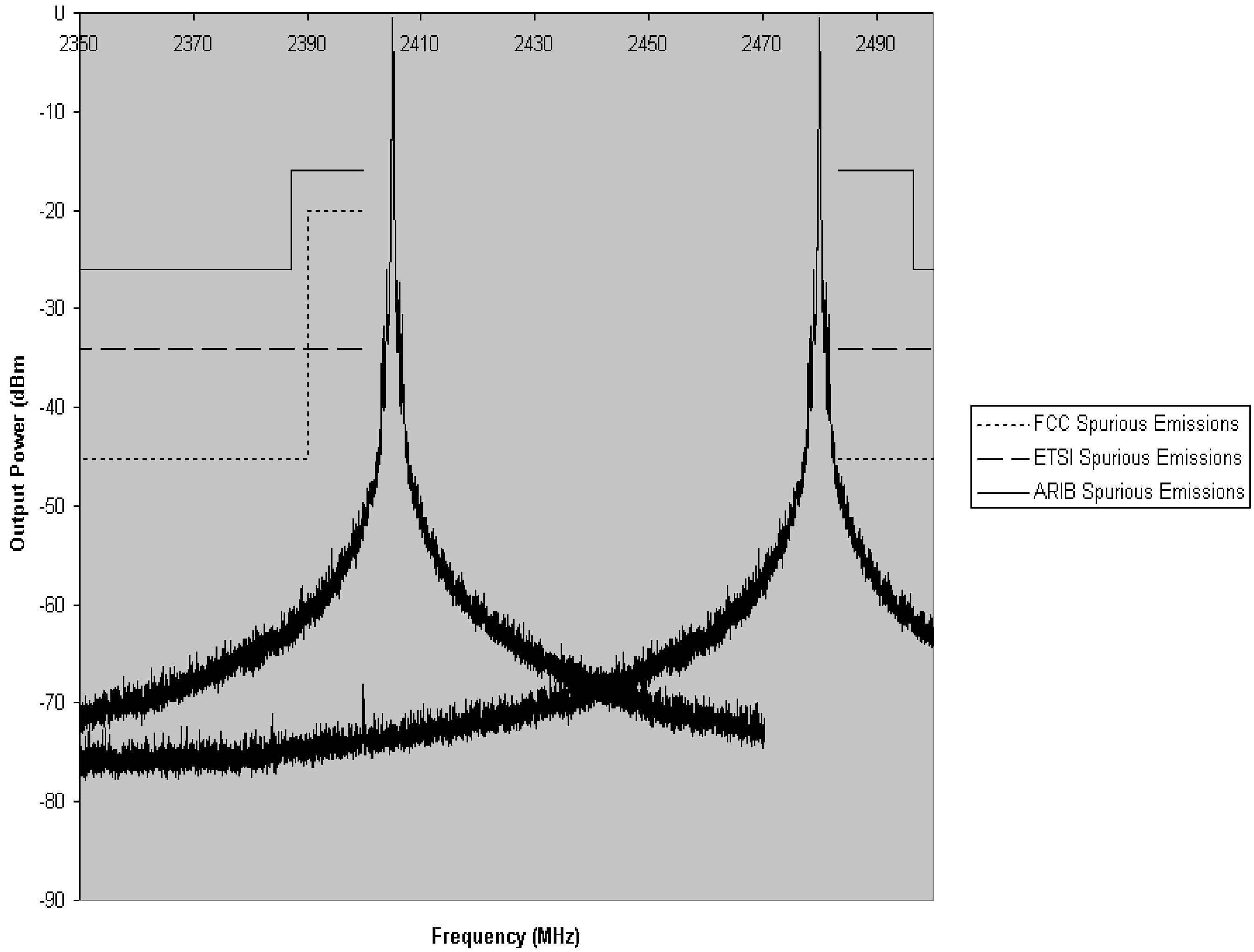

Figure 2. Spurious Emissions Limits on Upper and Lower Channels

Figure 3 shows the 2480MHz modulated carrier in a 10MHz span. The spurious limits from the regulatory bodies are superimposed on the spectrum, which fails FCC spurious emission requirements for a 100% duty cycle. There is more margin available against the ETSI and ARIB requirements. The non-ideal behavior of the spectrum is due to the following:

- Modulation sideband spectral regrowth
- Phase noise
- Switching noise

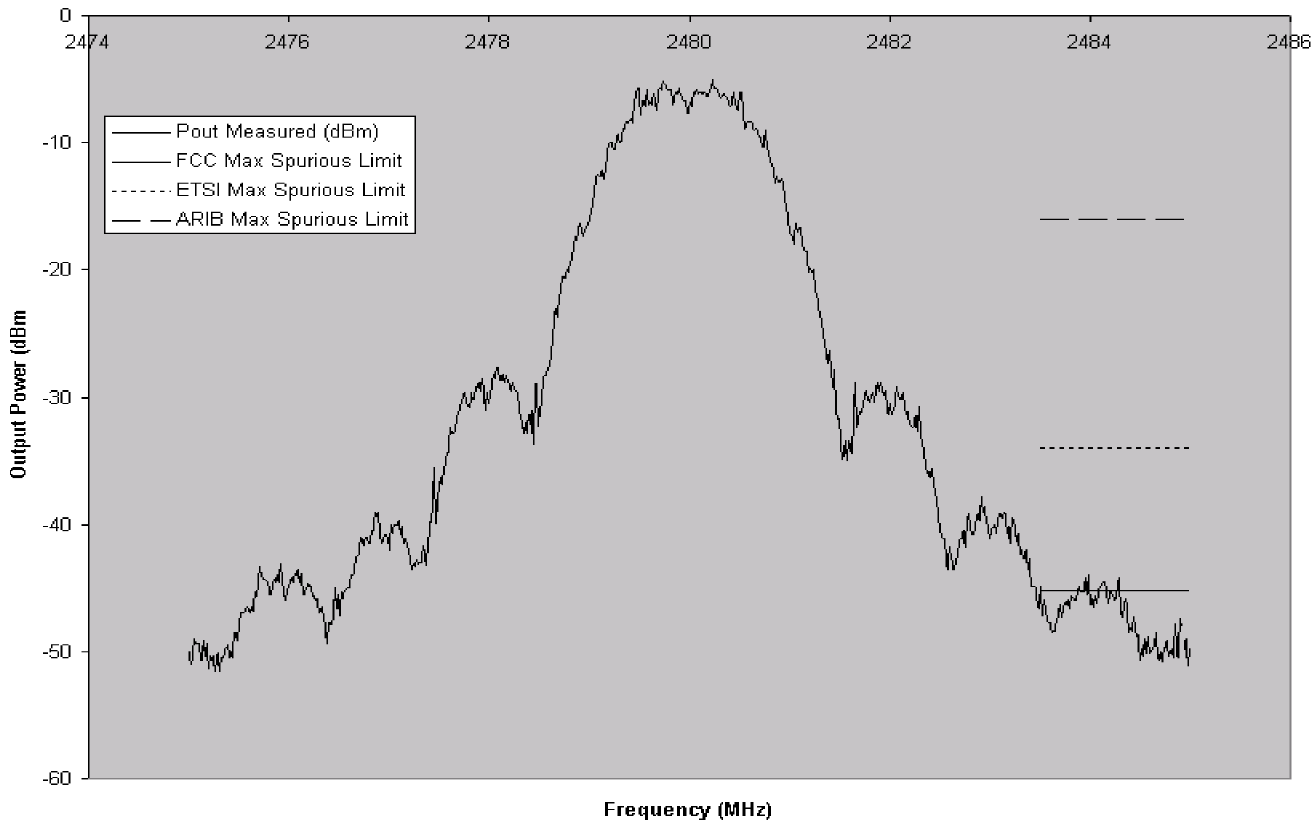

Figure 3. Spurious Emissions Limits on Modulated Spectrum (2480MHz)

Table 3. Margin to Regulatory Body Spurious Emission Limits

Regulatory Body	Margin (dB)
FCC	none
ETSI	11
ARIB	29

Even the perfect theoretical IEEE 802.15.4 waveform has limited margin vs. the FCC requirements for a 100% duty cycle.

If the duty cycle is reduced from 100%, then the spurious emissions limits are effectively increased and more transmitter output power is allowed for FCC requirements. The majority of IEEE 802.15.4 applications can make use of the increased spurious emissions limits due to extremely low duty cycles. Table 4 shows the increase in output gain that is allowable through duty cycle reduction.

Table 4. Margin with Various FCC Duty Cycles

FCC Duty Cycle	Margin (dB)
100%	none
30%	10
10%	20

20Db is the maximum relaxation allowed by the FCC for duty cycle.

If the application tolerates disuse or reduced power of the upper channels and the lowest channel, even more transmitter output power will be allowed. Table 5 and Figure 4 show these values.

Table 5. Margin with Various Frequency Channels

Frequency Channel (MHz)	Margin (dB)
2470	12
2475	6
2480	none

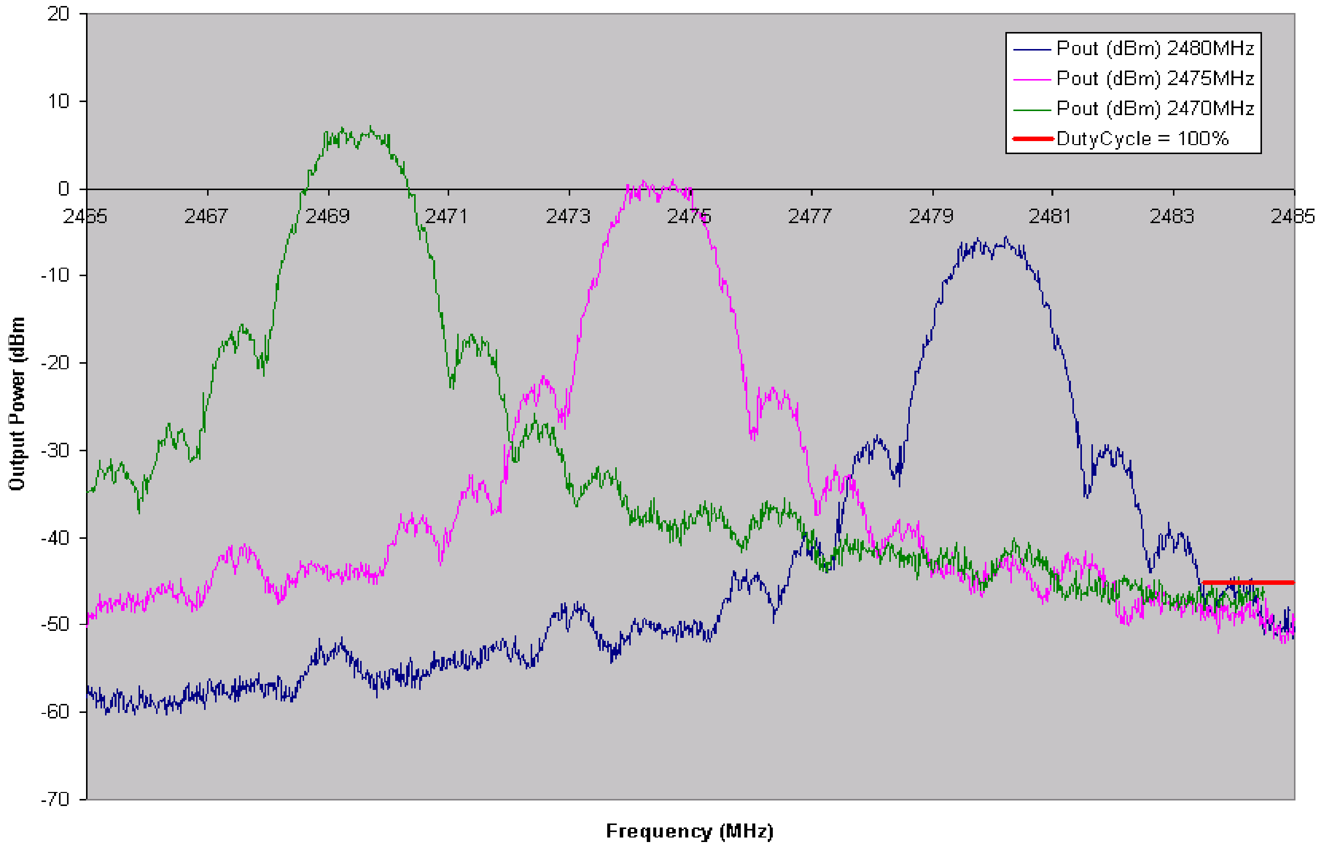

Figure 4. Increase in Output Power vs. Frequency Channel

Capability of operation on all channels is required to be fully IEEE 802.15.4 compliant. However, different transmit power levels can be used on different channels.

The addition of an external PA could result in harmonics that exceed the spurious emissions limits imposed by the regulatory bodies. For example, both the 2nd and 3rd harmonics fall in the FCC restricted spurious emissions bands. As the duty cycle is reduced, an increase in harmonic power is allowed as shown in Figure 5 for FCC requirements. Duty cycle reduction and/or the use of a low-pass or band-pass output filter may be necessary. There are small and efficient ceramic monolithic devices manufactured by a range of suppliers. The manufacturers can assist in selecting the proper device for a given application. (See Section 4.3, “Ceramic Filters”.) In some cases, a lumped-element LC filter may be adequate.

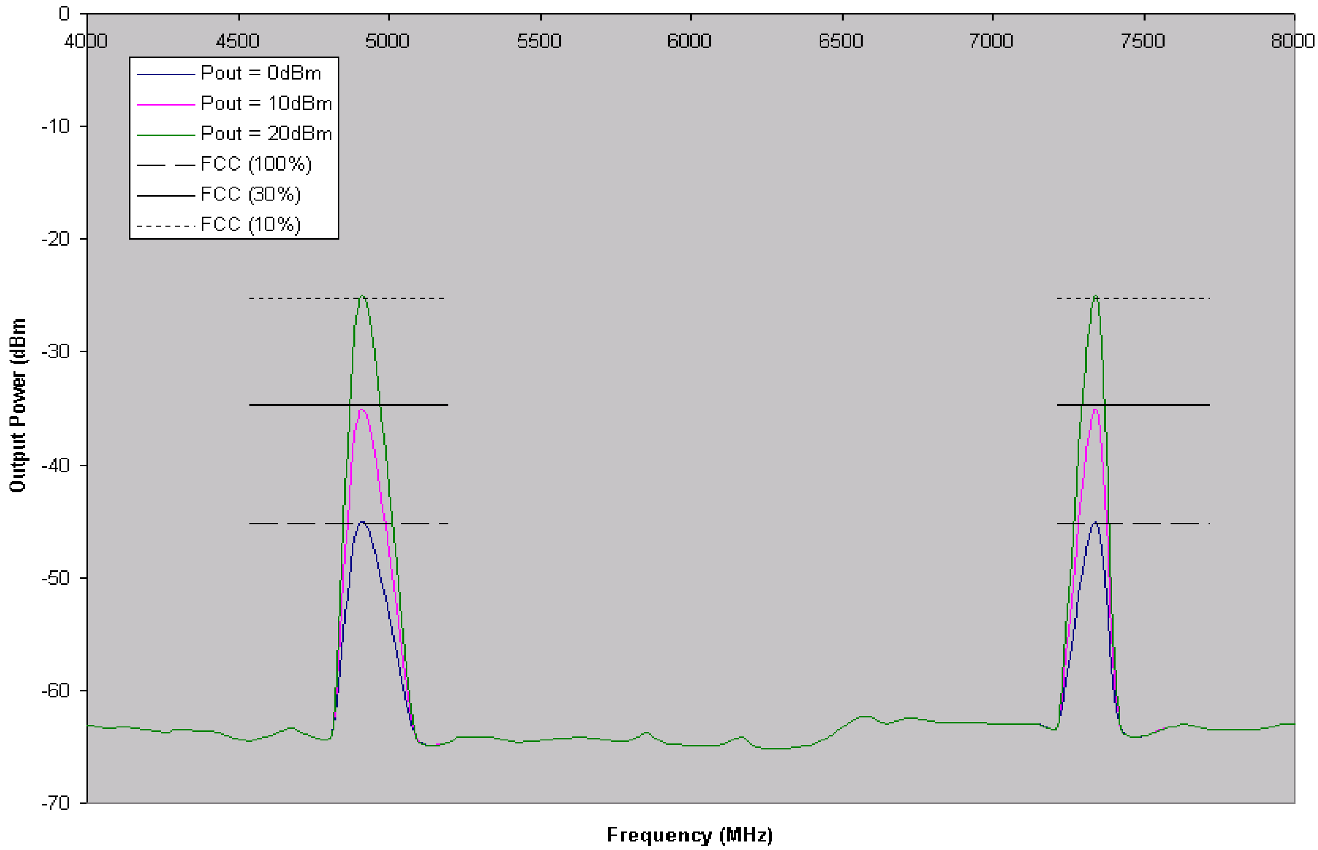

Figure 5. Spurious Emissions Limits on 2nd and 3rd Harmonics

3 Practical Test Implications

The standards cited in this note specify the transmitter output power and spurious emissions limits that the unit under test is required to pass in order to be certified. At first glance, it appears to be simple exercise to calculate the maximum output power allowed, but there are a range of factors that complicate matters. The following sections describe these factors.

3.1 Antenna Gain

Some of the regulatory testing is performed as radiated tests, and the gain of the antenna at the frequency of interest becomes a factor in the measurements. Gain for an embedded antenna can vary considerably, from less than –5 dBi to more than 5 dBi, even on simple antennas. This could result in more than 10 dB of difference from one design or layout to another, even for an identical transmitter.

3.2 Measurement Accuracy

RF measurements are always subject to some tolerance. Even with careful calibration, conducted tests at two different test houses can show more than 2 dB of difference.

Radiated tests are subject to even higher tolerances, and the repeatability of these measurements is worse than conducted measurements.

3.3 Test Setup

The test set-up parameters (bandwidth, sweep time, trace parameters, etc) may significantly affect the measured values and cannot be controlled by Freescale, as these are determined by the particular test case and test house. Consequently, tests results vary considerably from one test house to another.

Freescale recommends that when a PA is used the relevant test house be contacted early in the design process and preliminary tests be performed on prototype samples. The measured results from the test house will indicate the power level that may be allowed in the final product.

3.4 PCB Layout and Shielding

Some harmonic emissions can radiate directly from PCB traces themselves. This is because a trace that is electrically short at 2.4 GHz may approach 1/4 or 1/2 wave at a harmonic frequency. This is especially true for the higher harmonics.

Also, a metal shield that is effective at 2.4 GHz may provide less attenuation at a harmonic frequency. This depends on the design itself and how it is attached.

3.5 Component Selection

Component selection can also be an important factor. For example, most ceramic monolithic baluns provide a degree of harmonic attenuation inherent to the design. However, the degree of attenuation can vary from one component vendor to another.

Another item to consider is that PA matching components built by different vendors may have identical performance at 2.4 GHz, but their performance at harmonic frequencies can vary a great deal. This means that identical parts from different vendors can produce different transmitter harmonic levels.

4 Device Examples

An external LNA may be used in addition to a PA to increase range. The LNA has the obvious advantage of not being constrained by the regulatory standards that strictly limit the transmitter output power. This section describes some example LNAs, PAs, and ceramic filters.

4.1 LNA Devices

The increase in receiver sensitivity with the use of an external LNA is determined by the gain and noise figure of the LNA. If the LNA gain is adequate (>10 dB), the noise figure of the LNA will be the primary factor in determining the achievable sensitivity; thus, it becomes important to use a low noise LNA transistor.

The MC1319x evaluation board has an on-board LNA with a gain of approximately 10.5 dB. Measured sensitivity without the LNA was –95 dBm while measured sensitivity with the LNA was –103 dBm.

The increase in sensitivity with the use of the LNA resulted in an increase in range. (See Freescale Application note, AN2902.) This characterization was performed with no obstructions (line of sight) in a remote outdoor setting. Remember, if range is limited due to ambient noise and EMI in the 2.4 GHz band, such as that from heavy WLAN traffic, then an LNA may be of limited benefit.

Table 6 lists some LNA devices and some of their relevant specifications.

Table 6. LNA Devices

Vendor	Device	Gain	Noise Figure	Enable Pin?	Other Parameters
Freescale	MBC13720	12 dB	<3 dB	Yes	MMIC, low external parts count, bypass feature
NEC	NE661M04	13 dB	<1.6 dB	No	High performance, high frequency transistor
NEC	NE662M04	14.5 dB	<1.4	No	High performance, high frequency transistor
NEC	UPC8231TK	17.0 dB	<1.3 dB	Yes	MMIC, high gain
Infineon	BGA622	12 dB	<1.5 dB	No	Low external parts count
Infineon	BFP420	13.6 dB	<1.4 dB	No	High performance, high-frequency transistor
Phillips/NXP	BGA2012	11.5 dB	<2.5 dB	Yes	MMIC, low external parts count

4.2 PA Devices

A suitable PA device should be capable of supplying the requested output power, and should not degrade the transmitted signal. Because O-QPSK modulation is used for IEEE 802.15.4, a linear PA is required to avoid an increase in the sidebands and EVM. A PA device designed for Bluetooth applications can be used, but the output power will have to be reduced from the device rating listed for a Bluetooth signal.

Harmonics will increase with the use of a PA and these will need to be filtered out.

Table 7 lists devices with their respective output 1 dB compression point. It may be possible to use these devices to the 1 dB compression point, but EVM and spurious emissions should always be checked for degradation compared to operation without a PA.

Table 7. PA Devices

Vendor	Device	Output 1 dB Compression Point
Freescale	MBC13720	14 dBm
Freescale	MMG2401	>20 dBm
NEC	UPG2301TQ	>22 dBm

4.3 Ceramic Filters

Table 8 shows commonly selected output ceramic filters for the ISM band.

Table 8. Ceramic Filters

Vendor	Device
Murata	LFB182G45SG9B740
Johanson	2450BP18C100A
Johanson	2450BP41D100B

5 Modules

Modular designs are currently available from several suppliers that include an external PA and/or LNA. Freescale strongly recommends that a small quantity of these be obtained, so that performance of designs with an external LNA and/or PA can be evaluated quickly in the intended application.

In some cases, rather than develop a new design in house, it may be an advantage to purchase a modular design, or to license the design of an existing module.

The following is a partial list of companies that produce modules with the Freescale series of IEEE 802.15.4 transceivers:

- L.S. Research (www.lsr.com)
- Maxstream (www.maxstream.com)
- Panasonic (www.digikey.com)

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