Freescale IEEE 802.15.4 / ZigBee Node RF Evaluation and Test Guidelines

Reference Manual

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About This Book

This manual describes Freescale's RF evaluation and test recommendations for developers of wireless IEEE 802.15.4 Standard nodes.

Audience

This manual is intended for system and hardware designers and test engineers responsible for developing products using Freescale IEEE 802.15.4 technology which supports various software applications including ZigBee, ZigBee RF4CE, and custom Freescale stacks.

Organization

Freescale provides a large number of design resources from reference manuals, reference designs, application notes, software applications and tools.

This document is organized as follows:

Chapter 1	Guidelines for the Successful Hardware Development of an IEEE 802.15.4 / ZigBee Wireless Node - Provides an overview of a recommended hardware design flow and makes designers aware of available Freescale design resources.
Chapter 2	RF Design Validation and Verification - Provide in depth means and methods for doing RF debug and evaluation including recommended equipment and available Freescale software tools.
Chapter 3	FCC Pre-Certification / Certification - Provide an overview of FCC certification requirements and process and discuss means and available tools to implement the process.
Chapter 4	Production Test Guidelines - Describes manufacturing test recommendations for products that employ Freescale IEEE® 802.15.4 Standard wireless technology.
Appendix A	Freescale 802.15.4 RF Test Software - The RF test software ranges from simple standalone applications running on the target board to more capable and sophisticated tools that use a client application running on the target board with host application running on a personal computer (PC).
Appendix B	RF Test Modes in The MC1320x and MC1321x Transceivers - Provides reference information on the listed devices for enabling RF test modes.

Revision History

The following table summarizes revisions to this document since the previous release (Rev 0.0).

Revision History

Location	Revision
Entire Document	Updates throughout and added Chapter 4.

Definitions, Acronyms, and Abbreviations

The following list defines the acronyms and abbreviations used in this document.

ADC	Analog to Digital Converter
AES	Advanced Encryption Standard
ARM	Advanced RISC Machine
CTS	Clear to Send
DAC	Digital to Analog Converter
DCCF	Duty Cycle Correction Factor
DMA	Direct Memory Access
I2C	Inter-Integrated Circuit is a multi-master serial computer bus
ISM	Industrial Scientific Medical 2.4 GHz radio frequency band
JTAG	Joint Test Action Group
LGA	Land Grid Array
MAC	Media Access Controller
MCU	Microcontroller Unit
NEXUS	An embedded processor development tool interface that helps design engineers identify software and hardware-level issues.
PCB	Printed circuit board
PiP	Platform in Package
PSDU	PHY service data unit
PWM	Pulse-width modulation
RTS	Request to Send
SMA Connector	SubMiniature version "A" connector
Single-ended	An RF port on a transceiver that is a single input/output pin as opposed to a differential RF port.
SPI	Serial Peripheral Interface
SSI	Synchronous Serial Interface
TACT Switch	A switch that provides a slight "snap" or "click" to the user to indicate function.
Target Application	Customer specific application intended for the customer module
TELCO	Telephone Company
USB	Universal Serial Bus
VCP	Virtual Com Port

Recommended References and Reading

- "Simplifying FCC Compliance for 802.15.4 2.4 GHz devices", National Technical Systems, www.ntscorp.com

- ETSI EN 300 440-1, V1.3.1 (2001-9), "Electromagnetic compatibility and Radio spectrum Matters (ERM); Short range devices; Radio equipment to be used in the 1 GHz to 40 GHz frequency range; Part 1: Technical characteristics and test methods", European Standard (Telecommunications series), Reference REN/ERM-RP08-0406-1.

- Code of Federal Regulations Title 47 - Telecommunication: Part 15 - Radio Frequency Devices. Available in electronic and PDF formats from the FCC web site.

- "Measurement of Digital Transmission Systems Operating under Section 15.247" FCC Publication 558074.

Chapter 1
Guidelines for the Successful Hardware Development of an IEEE 802.15.4 / ZigBee Wireless Node

1.1 Introduction

The growth of low cost, low power wireless nodes based on the IEEE® 802.15.4 Standard has been expanding rapidly. Freescale provides devices, software, platforms, and extensive design collateral to ease design development, speed time-to-market, and minimize design errors. A 2.4 GHz wireless node, however, can be somewhat intimidating to those users that have had little or no experience with RF design. The good news is that RF circuitry is minimized by today's integrated radios and that Freescale provides extensive design support for the user.

The purpose of this manual is to help guide the new user of Freescale 802.15.4 devices (radios) through the process of turning their application into a qualified printed circuit board (PCB) by understanding the potential pitfalls of RF design and by using the Freescale design aids. A simple hardware design flow is presented with emphasis on radio design and testing.

1.2 Design Flow Overview

The designer is encouraged to use the following simplified design flow that emphasizes the hardware RF considerations:

1. **Determine which Freescale device/platform best meets the user's needs** - Freescale supplies three primary families of devices (see Table 1-1). Software stacks, development boards/kits, and design collateral are available for all these families. It is not the intent of this manual to help determine this selection, other than to emphasize this as a first step.

Table 1-1. Summary of Freescale IEEE® 802.15.4 Families

Family	Description	Comments
MC1320x	Fully compliant 802.15.4 transceiver (no onboard MCU)	• Freescale stacks support 8-bit MC9S08x including the MC9S08QE128 • Usable with other Freescale MCUs
MC1321x	Fully compliant 802.15.4 transceiver (MC13202 equivalent) integrated with a MC9S08A MCU die in a single package	• Freescale stacks fully support this device • Standalone device - needs no other MCU • Based on the 8-bit MC9S08 MCU
MC1322x	Fully integrated ARM7 MCU and transceiver in a single device.	• Freescale stacks fully support this device • Standalone device - needs no other MCU • Based on the 32-bit ARM7 MCU • Lowest power

2. **Select a Freescale Reference Design as a baseline for a board schematic and layout** - Freescale has specific reference designs available for ALL devices and their variations with regard to antenna and board types. Freescale emphasizes the importance of using reference designs to achieve a quick-turn, successful target PCB.

— Reference designs have been built and verified. RF performance is greatly impacted by board parameters (metal/dielectric thickness, permittivity, and stackup), component placement, interconnect geometries, and ground topology

— Complete design databases and documentation are provided including schematics and layouts as well as BeeKit configuration files for easy integration into the BeeKit environment

— The package footprints on the reference layouts have been designed for reliable solder reflow processes

— The reference design can be used "as-is" for simple applications or used as a starting point for the board stackup, RF circuitry placement and design, and the 802.15.4 device layout. From the starting point the user can then expand the design to include his unique peripheral devices and circuitry.

— Reference designs vary from full featured development boards to minimal area, simple modules

— Both 2-layer and 4-layer metal designs are available

Table 1-2 is a summary list of available reference designs.

NOTE

This may not be a comprehensive list. Check with the Freescale website www.freescale.com/zigbee under "802.15.4 and ZigBee® Hardware Reference Designs" for a current list of available designs. There are two types of reference designs listed:

• Module Reference Design - that contains a minimal amount of peripheral circuitry

• Development Board Reference Design - that document Freescale's 802.15.4 development hardware.

It is recommended that a Module Reference Design be selected as the starting point for an OEM design.

Table 1-2. Summary of Freescale 802.15.4 and ZigBee® Hardware Reference Designs

Reference Design	Family	Description
1320x-RFC	MC1320x	Transceiver only development board reference design. Daughter card for use with an MCU.
1320x-QE128-EVB	MC1320x	Development board reference design for MC1320x and MC9S08QE128
1320x-QE128-IPB	MC1320x	Module reference design for MC1320x and MC9S08QE128 using an RF interface with a balun and PCB "F" antenna
1321x-SRB	MC1321x	Development board reference design for sensor node

Table 1-2. Summary of Freescale 802.15.4 and ZigBee® Hardware Reference Designs

Reference Design	Family	Description
1321x-NCB	MC1321x	Development board reference design for network node
1321x-IPB	MC1321x	Module reference design for MC1321x using RF interface with a PCB "F" antenna
1321x-ICB	MC1321x	Module reference design for MC1321x using an RF interface with a balun and a chip antenna
1321x-USB	MC1321x	USB stick reference design for MC1321x using an RF interface with a balun and a chip antenna
1322x-SRB	MC1322x	Development board reference design for sensor node
1322x-NCB	MC1322x	Development board reference design for network node
1322x-USB	MC1322x	Development board reference design for USB stick
1322x-LPB	MC1322x	Development board reference design for low power node
1322x-IPB	MC1322x	Module reference design for MC1322x using single-ended RF interface with a PCB "F" antenna
1322x-ICB	MC1322x	Module reference design for MC1321x using single-ended RF interface with a chip antenna

3. **Design/layout target application board using the selected Reference Design baseline** - For simple end node applications a reference design such as an "IPB" or "ICB" may be very close to the desired final product. In contrast, a complex network coordinator node may take advantage of a more complex reference design such as an "NCB" or "SRB" with major modifications. Key points to consider:

— Use the provided 802.15.4 device package footprint including crystal, and power supply connections.

— Use RF components, layout, and board stackup as provided. Dielectric thickness is part of the antenna design. Changing the thickness will require antenna tuning that is beyond the scope of this application note.

— For each Freescale 802.15.4 device there is a respective Reference Manual, The "System Considerations" chapter is an excellent source of design considerations.

— Use a properly specified or recommended crystal for the reference oscillator (see AN3251, "Reference Oscillator Crystal Requirements for the MC1319x, MC1320x, MC1321x, and MC1322x").

— Prepare for official certification

– Choose a certification house as a partner (see Section 3.2.1, "Choosing the Correct Certification Lab is Important") early in the process

– Solicit advice for RF requirements for targeted market countries

— Adding test points or connectors for the following can assist RF test:

– Reference clock output (CLKO for HC9S08/transceiver platforms or TMR1 for MC1322x platforms)

– UART port (include flow control)

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— Consider adding design accommodations such as test points and others connections for RF test.

— Modify or add to the reference design peripheral circuitry as required by the target application. For designs using the MC1320x devices, the signal connections between the transceiver and target MCU should be left "as-is" so that porting Freescale-supplied applications is simplified as much as possible.

NOTE

In addition to specific device data sheets and reference manuals, Freescale provides extensive support material to assist design decisions. Table 1-3 provides only a partial list of relevant support documentation. The user is encouraged to scan the Freescale documentation available at www.freescale.com/zigbee for additional material that may be use to a particular application.

Table 1-3. Relevant 802.15.4 Hardware Design Resources

ID	Title	Description
ZHDCRM	Freescale IEEE 802.15.4 / ZigBee Hardware Design Considerations Reference Manual	• Provides package information including metal layout, solder mask, and solder paste recommendation. • Solder reflow recommendations • Tape and reel info • **Key chapter on RF design and layout considerations**
AN2975	Range Extension for IEEE® 802.15.4 and ZigBee™ Applications	application note defines IEEE 802.15.4 PHY layer parameters and provides discussion of RF component selection
AN2731	Compact Integrated Antennas - Designs and Applications for the MC1319x, MC1320x, and MC1321x	• application note discusses use and tradeoffs of different antenna types • Provides detailed information on Freescale's recommended "F" antenna
AN3251	Reference Oscillator Crystal Requirements for the MC1319x, MC1320x, MC1321x, and MC1322x	application note provides crystal specifications, recommended crystals, and design information for all Freescale 802.15.4 device reference oscillator crystals

4. **Build prototype PCB; debug and evaluate/verify RF performance** - After the design is complete, first prototype boards are built. A structured approach is suggested for debug (as opposed to first loading the target software and trying to do debug with the complete application):

— Do an initial visual inspection

– Are all required components in place?

– Inspect the 802.15.4 device and the reference crystal for orientation. With a square package outline, it is not uncommon for components to be improper placed; rotated by 90°

— Power-up the board and check power supply(s)

– Are voltages correct?

– Are currents within expectations?

– Are all VDD supply pins getting voltage (any opens)?

– Are there any shorts?

— Check basic operation with and w/o reset active
  – With reset active, is current draw within expectation?
  – After release of reset, does the MCU or device reference oscillator start properly and is it on frequency?
— Establish connection between the development tools and the debug port
  – With MC9S08 platforms this is the BDM port
  – With the MC1322x platform this is the ARM7 JTAG port
  – Download a simple test application and establish communication and control of the target board

NOTE

For prototype boards:

- First builds for new process flows are recommended to be a limited number of boards
- The 802.15.4 device packages are small and have small pads/pins with tight pad pitch
- Solder reflow temperatures are limited to 260°C or less. This requires that reflow temperature profiles be carefully developed and maintained because RoHS standards use higher temperature solder.

Because of these factors, it is possible to have opens or shorts with the device connections. If initial target board failures are found, first thoroughly investigate device connections for opens and shorts because the manufacturing process may need adjusting.

At this juncture, once proto boards are generally functional, common practice is to continue development in a somewhat parallel approach:

— Provide boards for software development
— Debug custom application hardware (sensors, peripherals, power management, etc)
— Test and evaluate RF performance

It is to be emphasized that the RF test and evaluation should be a separate focused activity and independent of the user's target software. This is possible because Freescale provides software tools/applications for test that are easily applied to the target board. In this manner basic RF operation can be evaluated in a methodical manner and any impact from the target software can be eliminated.

5. **Design Phase RF test and evaluation** - This activity will first evaluate transmitter and receiver performance. Once these are independently evaluated, and corrected as needed, end-to-end RF performance is checked via packet error rate (PER) testing. Chapter 2 of this reference manual is an in-depth discussion of testing techniques and tools for developing a qualified RF design.

6. **FCC pre-certification / certification** - Once the RF and application performance of the target board is considered qualified, a wireless product must become government certified for the countries / markets in which the product will be sold. In the United Stated the product must be Federal Communications Commission (FCC) certified. This process is generally considered a

two-stage process consisting of pre-certification and actual certification. Chapter 3 of this reference manual is an in-depth discussion of the certification process and available Freescale tools that can assist in certification of wireless design.

7. **Production test** - Test during production must verify operation of the module with a minimum of test time and resources to keep cost low, but still provide suitable validation. Chapter 4 of this reference manual is a discussion of the suggested techniques and recommended software applications that can be modified for customer use.

1.3   What This Reference Manual Covers

Although this chapter presents a recommended hardware design flow, the manual is not intended as an applications "how to" design guide. The following chapters on RF evaluation and certification do provide hands-on information about equipment, tools, and means to debug and qualify the RF circuitry, and then officially FCC certify a final product. As a final subject, the manual provides information and guidelines for production test.

Chapter 2
RF Design Validation and Verification

2.1　Introduction

As covered in Chapter 1, RF test and evaluation should be done as a separately focused activity. This should be performed to eliminate any possible dependencies between software and hardware. It is best that software used to evaluate RF performance be simple test application(s), not the target communications software where there can be unknowns as to the source of any problems.

RF functionality can be tested in an orderly manner. Very simplistically, there is:

- RF transmission (TX)
- Reception (RX)
- End-to-end performance

A wireless node can only be doing one function at-a-time, i.e., transmission or reception. Each can be evaluated independently, and then, the complete end-to-end connection can be evaluated.

Before proceeding with RF test, consider the following:

- It is recommended that the test engineer have a good working knowledge of the IEEE® 802.15.4 Standard PHY layer specification:

IEEE Std 802.15.4™-2003, Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs), 2006

The 802.15.4 PHY has several frequency bands, but the devices of interest deal only with the 2450 MHz PHY. The user should become familiar with all the details of over-the-air signals; modulation means and spectrum, packet construction and format, transmitter and receiver specifications, etc.

- RF characteristics can be measured by two general means, i.e., over-the-air and direct connection. Direct connection is highly recommended because over-the-air measurements are very difficult to perform as well as quantify; over-the-air performance is highly dependent on antenna efficiency, direction, distance between the TX node and the RX node, and environmental interference. The purpose here is to measure the quality of the RF signal at the antenna.

- Use a Freescale provided software tool/application as a starting point for developing RF test applications. The suggested software is discussed in a following section. Also, using test software (which is required) implies some level of software support to the RF test engineer.

NOTE

Although the onboard RF circuitry of the 802.15.4 platforms and available Freescale applications support helps minimize the design and test effort to produce a working 2.4 GHz wireless node, it still requires a serious commitment in resources and equipment to validate and support the final RF design. If the user has minimal or no previous experience with RF design and test, he can consider using consulting services and/or pre-manufactured and certified modules as an end-use alternative.

2.2 Preparing for RF Testing

Once the module has been through preliminary debug and functional verification (as explained in Step 4 of the basic design flow), some suggested preparation for RF testing is presented in this section.

2.2.1 RF Test Equipment

To do RF test at 2.4 GHz frequency requires having some minimal level of required equipment which can be expensive, so the rent vs. buy option may be considered by the user.

A minimal list of measurement equipment is suggested in Table 2-1. The listed instruments or equivalent equipment is suitable.

Table 2-1. Typical Equipment Options for PHY Layer Tests

Type	Quantity	Vendor Options		Comments
		Model Number	**Manufacturer**	
RF Power Meter	1	E441X	Agilent	
Signal Generator	2	SMIQ Family	Rhode & Schwarz	Requires user programming
		SMU200A	Rhode & Schwarz	Requires user programming. application note available
		E443X	Agilent	Requires user programming
		N4010A	Agilent	Option 102 available for 802.15.4
Frequency Counter	1	53181A	Agilent	RF Frequency counter
Power Meter Sensor	1	E9323A	Agilent	
Vector Signal Analyzer	1	N9020A	Agilent	
		N4010A	Agilent	
Digital Multimeter	1	Any		
Integrated 802.15.4 Test Set	1			Custom

2.2.2 Preparing the Module for RF Test

Quantified RF measurements are best done via a connected path rather than over-the-air means. This requires that some form of hardwired connection be available on the board to attach equipment. There are several common ways this may be achieved:

- The board layout provides a wiring option for an RF connector - In this situation, the RF signal trace is ac-coupled through a capacitor to the antenna, and a second path to a connector (typically an SMA connector) is also available via an ac-coupled option. When using the board for test, the coupling cap to the antenna is removed, and the path to the RF connector is enabled through a second coupling cap. The connector must also typically be mounted as it is not normally in place. In order to minimize unwanted RF effects, it is best to share the common side of the capacitor pads This avoids having an open circuit stub hanging off of the RF path not used.
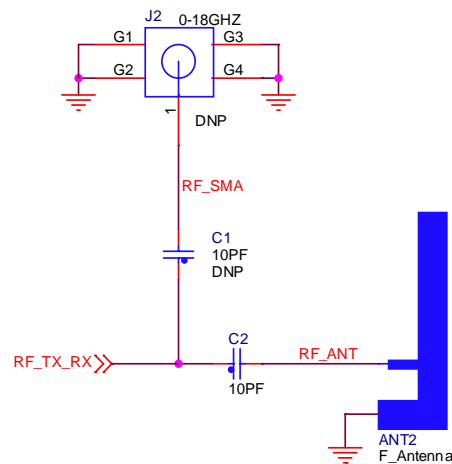
Figure 2-1. Wiring Option for RF Connector

- A special "microwave coaxial connector with switch" (similar to the Murata MM8130-2600 or Amphenol MCX series) can be inserted between the RF signal trace and the antenna - This is also a design/layout option that must be part of the board design. This connector/switch is surface mounted and normally sits in the RF signal path. When a special measurement probe is attached, the signal path to the antenna is opened and connected through the probe. In this manner, there is no board alteration done and good RF connection is made. This approach does have the disadvantage of being more expensive. However, it is possible to replace the connector with a capacitor for production runs.
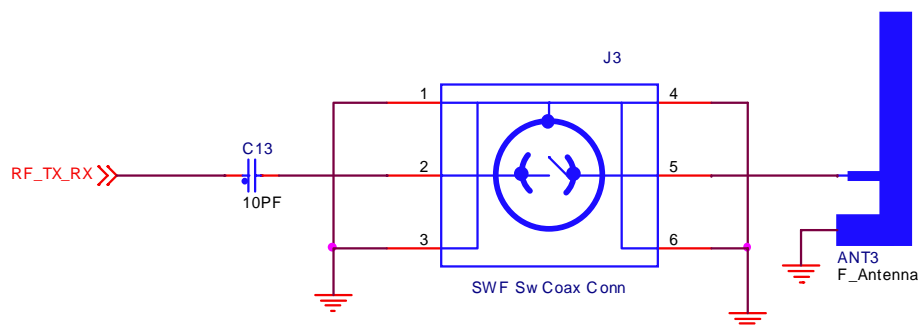
Figure 2-2. In-line Coaxial Connector with Switch

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- Altering the board for test purposes - an RF connector (typically SMA) can be soldered to the board and connected to the RF signal trace. Two general means are used to do this:
  — The connector is soldered to the board via very short "pigtails". The ground shield connection should be as short as possible or can be soldered directly to the board ground. The RF signal should be wired to the RF connector center conductor with as short a wire as possible.
  — Cut away the antenna (in these examples, an "F"-antenna is used) such that the SMA connector center conductor can be directly soldered to the antenna feed wire and the connector ground is directly wired to the board ground.

2.2.3   Crystal Reference Oscillator Characterization and Trim

The IEEE 802.15.4 Standard requires that the frequencies and symbol rates associated with the radio transmit and receive functions have an accuracy of +/-40ppm or better. With properly specified crystals, the Freescale devices can maintain a typical accuracy of +/-30ppm or better over temperature and voltage variation.

At this juncture, it is recommended that the reference oscillator of the target be characterized, and as required, the nominal frequency be centered for the MC1320x, MC1321x, and MC1322x devices.

NOTE

> The following sections describe general procedures for characterizing the device reference oscillator. Different software tools provide capability to adjust the oscillator trim capacitance and monitor the reference oscillator accuracy (ppm). The user should refer to the particular application reference documentation for details on using that application (see Table A-1).

2.2.3.1   MC1320x and MC1321x 16MHz Transceiver Reference Oscillator Characterization

The 20x and 21x devices have a fixed 16MHz reference oscillator. The capacitive loading for the oscillator is provided primarily by discrete capacitors (see AN3251, "Reference Oscillator Crystal Requirements for the MC1319x, MC1320x, MC1321x, and MC1322x") and is trimmed by onboard capacitors.

To characterize the oscillator performance:
- The device initializes with the onboard trim capacitance set to mid-range (SPI Register 0x0F, Bits[15-8] = 0x7F), i.e., about 2.4pF per side. At first, do not alter the default value.
- Monitor the frequency accuracy at output pin CLKO. The desired accuracy is less than +/-5ppm without altering the default onboard trim.
- As required, adjust the external load capacitors to center the reference frequency as close to nominal as possible. Increasing capacitance lowers frequency.
- Once the discrete load capacitance is determined, the trim value can be adjusted to "zero" the frequency error.

NOTE

With prototype modules, these results should be checked across several boards. Later, when production volume is imminent characterizing the reference oscillator across a large sample of modules is recommended to determine typical variation and any in-production test or correction.

2.2.3.2   MC1322x 24MHz (Nominal) Reference Oscillator Characterization

The 22x device has a nominal 24MHz reference oscillator (this frequency is most common although 13-26MHz is usable). The capacitive loading for the oscillator is provided and trimmed completely by onboard capacitors.

To characterize the oscillator performance:

- Out of reset, the device initializes with the onboard trim capacitance set to no load (Register XTAL_CNTL 0x8000_3040, Bits[25-16] = 0x000). However, the software application usually initializes the crystal tuning with a default value that is determined when the application is configured at compile time.
- Monitor the frequency accuracy at a timer output pin (TMRx) as determined by the application software, typically TMR1. The MC1322x has no dedicated clock output monitor pin, so this function must be provided by a counter as enabled by the test software.
- Adjust the onboard load capacitance to center the reference frequency as close to nominal as possible. Increasing capacitance lowers frequency.

NOTE

With prototype modules, these results should be checked across several boards. Later, when ramping up production, characterizing the reference oscillator across a large sample of modules is recommended to determine typical variation and any in-production test or correction.

2.3   Transmitter (TX) Tests

The transmitter test list includes the following parameter measurements:

- Transmit Power
- Out-of-band Spectrum

NOTE

The TX test descriptions give general test background and procedures. However, use the Freescale provided test software to establish these conditions.

2.3.1   TX Measurement Equipment

The required equipment list for the transmitter tests is shown in Table 2-2. All measurements may be done with a spectrum analyzer or a vector signal analyzer (VSA). The Error Vector Magnitude (EVM) measurements must be done on the VSA.

Table 2-2. Equipment Required for Transmitter Tests

Test Parameter	Spectrum Analyzer	Vector Signal Analyzer
Power Spectral Density	1	1
Error Vector Magnitude		1
Transmit Center Frequency Tolerance	1	1
Transmit Power	1	1

2.3.2   Transmit Power

The following quoted text is taken from the 802.15.4-2003 Standard:

"A compliant transmitter shall be capable of transmitting at least -3dBm. Devices should transmit lower power when possible in order to reduce interference to other devices and systems. The maximum transmit power is limited by local regulatory bodies."

NOTE

The 802.15.4 specification refers to power as measured using a "band power" technique with a 2 MHz bandwidth under modulated conditions. However, certification testing is measured as peak power so it is recommended that a peak power technique be used. This is the power measured using a spectrum analyzer or peak-reading power meter.

The nominal output power is typically 0dBm, and commonly, maximum output power is about +3 to +4dBm. This power may be specified at the package "edge" or to the antenna. Transmit power can be measured in various modes:

- Unmodulated Continuous (CW) - this mode produces the highest peak power with minimum channel bandwidth. This is also not a "real' operational mode, but it may be useful for debugging potential transmitter problems
- Modulated Continuous - this mode is useful for power measurement because it is continuous and modulated. However, the symbol stream may not be highly randomized. Use this mode for FCC pre-certification in Chapter 3, "FCC Pre-Certification/Certification"
- 9th Order Binary Polynomial (PRBS9) - this mode has a pseudo-random symbol stream that provides best observation of the modulation spectrum. It is normally a packetized mode, however and, the spectrum analyzer must be synchronized to the packets. Use this mode in Chapter 3 to determine Duty Cycle Correction Factor (DCCF)

The output power is measured using the following steps:

1. Set channel frequency.
2. Enable TX mode (typically either modulated continuous or PRBS9).
3. Enable the transmitter.
4. Measure output power on spectrum analyzer - Absolute peak power.
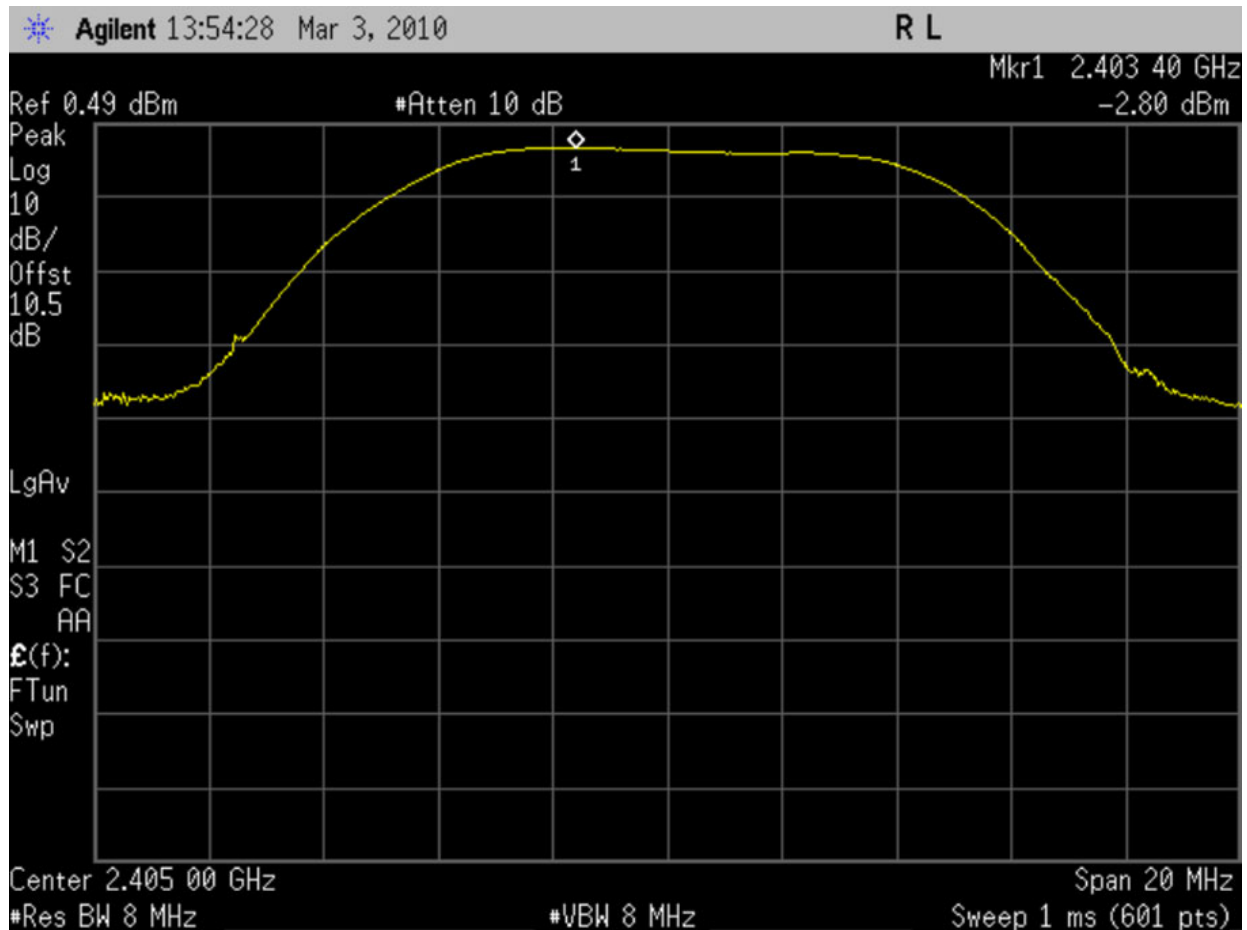
Figure 2-3. PRBS9 Signal with Synchronized Spectrum Analyzer

2.3.3   Out-of-Band Spectrum Measurement

The out-of-band spectrum requirements or spurious emissions are discussed extensively in Chapter 3 on FCC Certification. At this point in the module evaluation, it is recommended to take an initial look primarily at the TX spectrum 2nd and 3rd harmonics. The out-of-band spurious emissions including the 2nd and 3rd harmonics magnitude are required to be no greater than -41dBm absolute. Additional filtering for a harmonic may be required in the form of a frequency trap.

2.4   Receiver (RX) Tests

The receiver test list includes the following measurements:

- Packet Error Rate (PER) - is used as the measurement criteria for the following tests:
    — Receiver Sensitivity
    — Adjacent and Alternate Channel Rejection
- Energy Detect - is used as the measurement criteria for:
    — Clear Channel Assessment (CCA)

— Link Quality Indication

NOTE

The RX test descriptions give general test background and procedures, however, specific means of attaining the required transceiver state are not described as these are done via the test software in use.

2.4.1 Measurement Equipment

The test environment setup for receiver testing consists of one or two signal generators whose output are connected to the RF input of the receiver through a signal combiner. Testing is based on the concept of Packet Error Rate where a known good transmitter sends packets to the receiver/device under test (DUT). A vector signal generator is required to send/transmit the packets. Table 2-1 show four difference families of vector signal generators. These divide into two categories:

- Requires user programming for 802.15.4 protocol - manufacturers do have applications information available, but the user must program/setup the transmitter
  — 802.15.4 modulation scheme and proper type of filter
  — Proper packet size and format to meet the 802.15.4 Standard requirements for PER
- 802.15.4 support option available - the Agilent N4010A instrument does have a support option available.

NOTE

Programming of a specific signal generator is beyond the scope of this manual. It is the user's responsibility to provide the required functionality for 802.15.4 testing.

2.4.2 Packet Error Rate (PER) to Measure Receiver Sensitivity

Table 2-3 defines PER and receiver sensitivity and sets test conditions. PER uses a transmitter to send a stream of packets and the receiver is tested to see the "average fraction of transmitted packets that are not detected". The PER testing is qualified by the following;

- Packet size is set - the PHY Service Data Unit (PSDU) length = 20 octets (2 symbols)
- PER shall be < 1%
- Interference is not present

The measurement is conducted using a known good transmitting board connected to the test receiving unit via coaxial cable and an attenuator. The attenuator is used to set the desired power input level to the receiver at which the PER is to be measured. Consecutive passes at various power levels (attenuator settings) will be required to accurately measure the sensitivity.

Table 2-3. PER and Receiver Sensitivity Definitions

Term	Definition of Term	Conditions
Packet Error Rate (PER)	Average Fraction Of Transmitted Packets That Are Not Detected	Average Measured Over Random PSDU Data
Receiver sensitivity	Threshold input signal power that yields a specified packet error rate.	• PSDU length = 20 octets. • PER < 1%. • Power measured at antenna terminals. • Interference not present.

The following quoted text and table are also taken from the 802.15.4 Standard:

"Under the conditions specified in [Table 2-3], a compliant device shall be capable of achieving a sensitivity of -85 dBm or better."

A receiver sensitivity test cycle is composed of the following steps:

1. Set channel frequency
2. Enable the receiver
3. Signal generator sends random PSDU data
4. Received number of packets are tabulated; these are compared to transmitted number of packets to yield the PER percentage.

This cycle is repeated while altering the power level of the signal generator: the power level of the signal generator is lowered from a higher than -85dBm level in 1 to 2 dB steps until the PER < 1% is no longer measured at the receiver. This is the point of sensitivity.To clarify, the PER should be much lower than 1% at higher input power levels to the receiver. As the power level drops, the PER will rise and eventually equal or exceed 1% (the 802.15.4 Standard level). This then is the sensitivity of the device.

2.4.3   Energy Detect and Link Quality Indication (LQI)

The 802.15.4 receiver has the ability to measure the magnitude of the incoming signal energy (energy detection or ED) to the receiver at its programmed frequency. The energy is measured and reported via one of two mechanisms:

- Clear Channel Assessment (CCA) - the 802.15.4 PHY is based on a collision-avoidance protocol where the channel is tested for interference before enabling a transmission. A CCA execution enables the radio which does an energy detect on the channel and reports back to the higher layer function (MAC). The CCA measures channel energy and compares to a preset threshold.
- Link Quality Indicator (LQI) - this is a measurement of the energy strength or quality of a received packet. The LQI number is reported for each received packet. The 802.15.4 Standard requires that the LQI be scaled and limited to have a range of decimal 0 to 255. Values of LQI above approximately -30 to -25 dBm can be non-linear and should not be used as an indication of absolute received power.

NOTE

Refer Freescale's *802.15.4 MAC PHY Software Reference Manual,*
(802154MPSRM) to see how ED and LQI are reported in software.

The following quoted text is taken from the 802.15.4 Standard:

"The receiver energy detection (ED) measurement is intended for use by a network layer as part of a channel selection algorithm. It is an estimate of the received signal power within the bandwidth of an IEEE 802.15.4 channel. No attempt is made to identify or decode signals on the channel. The energy detection time shall be equal to 8 symbol periods.

The ED result shall be reported to the MLME using PLME-ED.confirm (6.2.2.4) as an 8-bit integer ranging from 0x00 to 0xff. The minimum ED value (0) shall indicate received power less than 10 dB above the specified receiver sensitivity (6.5.3.3 and 6.6.3.4), and the range of received power spanned by the ED values shall be at least 40 dB. Within this range the mapping from the received power in dB to ED value shall be linear with an accuracy of +/- 6 dB."

The following quoted text is taken from reference P802.15.4/D18-6.7.8 of the 802.15.4 Standard:

(6.7.8) "The link quality indication (LQI) measurement is a characterization of the strength and/or quality of a received packet. The measurement may be implemented using receiver energy detection, a signal-to-noise ratio estimation, or a combination of these. The use of the LQI result by the network or application layers is not specified in this standard.

The LQI measurement shall be performed for each received packet, and the result shall be reported to the MAC sublayer using PD-DATA.indication (6.2.1.3) as an integer ranging from 0x00 to 0xff. The minimum and maximum LQI values (0x00 and 0xff) should be associated with the lowest and highest quality IEEE 802.15.4 signals detectable by the receiver, and LQ values in between should be uniformly distributed between these two limits. At least 8 unique values of LQ shall be used."

To measure an LQI reported value:

- The signal generator sends a packet at a known power level on the receiver's channel frequency.
- The DUT receives the packet and reports the measured LQI level.
- The reported energy value is compared against the set input power level
  — The reported energy value should be within +/- 6dB of the actual input power level.
  — The reported value format will be in compliance with 802.15.4 Standard requirements.

2.5 Recommended Software for Validation and Verification

Appendix A, "Freescale 802.15.4 RF Test Software" provides a listing and overview of available Freescale applications suitable for RF validation and verification. Two basic appoaches to the evaluation software may be taken:

- Simple suite of test functions - available for either HCS08 (SMAC) or the ARM7 (22xSMAC) platforms, there are simple SMAC or 22xSMAC applications that provide basic RF test capability.
- Advantages of using these are:
  — Source code is available

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— They are easily modified and less sophisticated

— Lend themselves to "quick startup"

— They can use a simple UART or switch based control interface

— More suitable for simple board-to-board and range testing

— They can easily be extended for FCC testing

- Disadvantages include:

— Not as integrated approach as the following secondary approach

– More sophisticated, integrated test environment - also available for either HCS08 or the ARM7, the "ZigBee Test Client (ZTC) and Test Tool" environment is a more complete and capable test suite. The RF test capabilities are just a subset of the overall capability. If this approach is used initially for evaluation, it may eliminate a second learning curve for use of the software. One disadvantage can be that the more simple apps are more applicable for quick startup and easy test modification.

Regardless of the software choice, all of the applications are designed for board-to-board use. The user may be required to modify the applications to add control and synchronization to test equipment, especially for PER testing.

2.6   Board-to-Board / Range Testing

After initial evaluation and verification, board-to-board and range testing are needed to determine actual system performance. Board-to-board testing is the actual wireless, non-connected mode through the antennas. Antenna type, performance, and matching into the RF feed connection impacts overall end-to-end performance.

Once reasonable end-to-end performance is realized in the lab, range performance measurements can be useful to better evaluate overall system capabilities. As previously stated in this manual, quantifying actual RF power and receive sensitivity in a wireless environment can be very difficult, but comparative performance is more easily done and can be sufficient.

2.6.1   Evaluating Board-to-Board Performance

Board-to-board or range performance is similar to connected performance in that a given board is either receiving or transmitting. Performance in both modes must be evaluated in that receive sensitivity can be poor while transmit performance is proper, and the inverse can also be true. For brand new application boards that may not have been matched to the antenna, this is typically caused by different RF matching performance while in one mode versus the other.

To evaluate over-the-air performance, PER testing is again used. The difference between direct connected measurements and this over-the-air environment is that previously a generator provided the packet stream for the sensitivity test and a spectrum analyzer measured the transmitter characteristics. Now, direct board-to-board communication is used:

- For first evaluation of a new board, a known good reference module is recommended - Development modules are available from Freescale, and other universal modules are commercially available. The reference module can act as either the transmitter or receiver.

- Test software is a key component - Both sides of the RF link must have compatible test suites running the PER test. Typically conditions are similar to the IEEE 802.15.4 Standard where the PSDU size is 20 octets and the desired PER rate is 1% or less.

2.6.2   Using Freescale Software for Board-to-Board Testing

Board-to-board testing in the lab is the precursor to range testing (looking for the distance limit of the module). The general procedure is:

1. Load compatible PER target software into a transmit module and a receive module -
   — The transmit module can send a known number of packets of a known size
   — The receive module reports number of packets received, the LQI level, and other attributes.
2. Run the PER test and establish basic operation in both the receive mode and the transmit mode -
   — Initially in the lab, put the boards in close proximity to one another
   — Board orientation can be important due to the directionality attribute of the antenna
   — The PER test result should establish solid PER performance well below the 1% standard
   — LQI results can give a general indication of received signal strength

NOTE

It is important to note that LQI is a highly variable measurement, and not exact. The IEEE 802.15.4 Standard only requires that the measured LQI accuracy be within +/-6 dB of actual. Secondly, many variables impact received signal strength (antenna type, orientation, variation in TX output power, distance variation between units) and contribute to LQI variation

Running the applications first on two known good modules and observing the results can provide excellent background. These data can be used as a figure of merit for a similar target design.

3. If the PER testing does not give satisfactory results, the design must be debugged. Often for new designs, the RF impedance matching to the antenna is the most common culprit. In general, if receive performance is poor, then transmit performance will also be poor. However, this is not always the case where one mode gives good performance and not the other. Customers who copy the reference designs closely have been the most successful with first pass designs.

NOTE

Good practice is to assure that the PER TX application is supplying expected power to the antenna. This requires making a connected TX power measurement with the PER TX application. This is simply a double-check before trying to address a potential hardware problem.

Freescale provides two useful applications for board-to-board PER testing, dependent on platform:

- PER Test RX / PER Test TX (SMAC for HCS08 platform) - These are the RX application and the TX application for a basic packet error rate (PER) test. An individual test sends 1000 packets each with a 20-byte payload on a single channel. Although there is a standalone mode, a PC may be used for reporting test results. See Section A.2, "SMAC Test Applications for HCS08 Platform" for more details.

- Connectivity Test (22xSMAC for ARM7 platform) - This application allows evaluation of the basic connectivity with separate transmitter and receiver target modules. It supports PER test measuring the percentage of packet losses over a certain channel. LQI of each received packet is reported. Useful also for range test. A manual interface through push buttons or a menu driven serial interface port (UART) is supported. See Section A.1.2, "PC Host Application for Test (Test Tool)" for more details. Freescale highly recommends that customers load this software onto their applications, if at all possible, to validate the functionality of their hardware before loading their own application software.

2.6.3   Quantifying PER Test Results

Because there are so many variables regarding a wireless link, it is difficult to provide exact measurements of radiated power and over-the-air receiver sensitivity. An expensive, highly calibrated RF test environment is required, it is normally beyond the scope of a normal user, and fortunately really not necessary. The approach in this discussion is essentially a "relative" performance test where the DUT is compared against reasonable expected results.

Some contributing factors to RF link performance include:

- Transmitted power level - the actual transceiver output power may nominally be +/- 1 to 2 dB higher or lower than the expected programmed level
- Antenna performance - the RF matching (receive and transmit) to the transceiver, antenna gain, and radiation pattern affect radiated power and receive efficiency
- Signal propagation path - intervening obstacles such as walls, multi-path interference, and distance between nodes.
- Interference of other propagating signals
- Background noise
- Receiver Sensitivity

Given the above listed factors in a lab situation, the dominant factors are typically going to be the distance between the nodes (assuming little or no interference and an unobstructed signal path) and antenna effects.

2.6.3.1   Distance Between Nodes

The distance between nodes is typically the dominant source of reduced signal strength. Figure 2-4 shows calculated received power (dBm) versus range (meters) using a typical 0 dBm transmit output power. Observe that when power is measured in dB relative (as in dBc), it is a logarithmic scale versus the linear scale for distance.
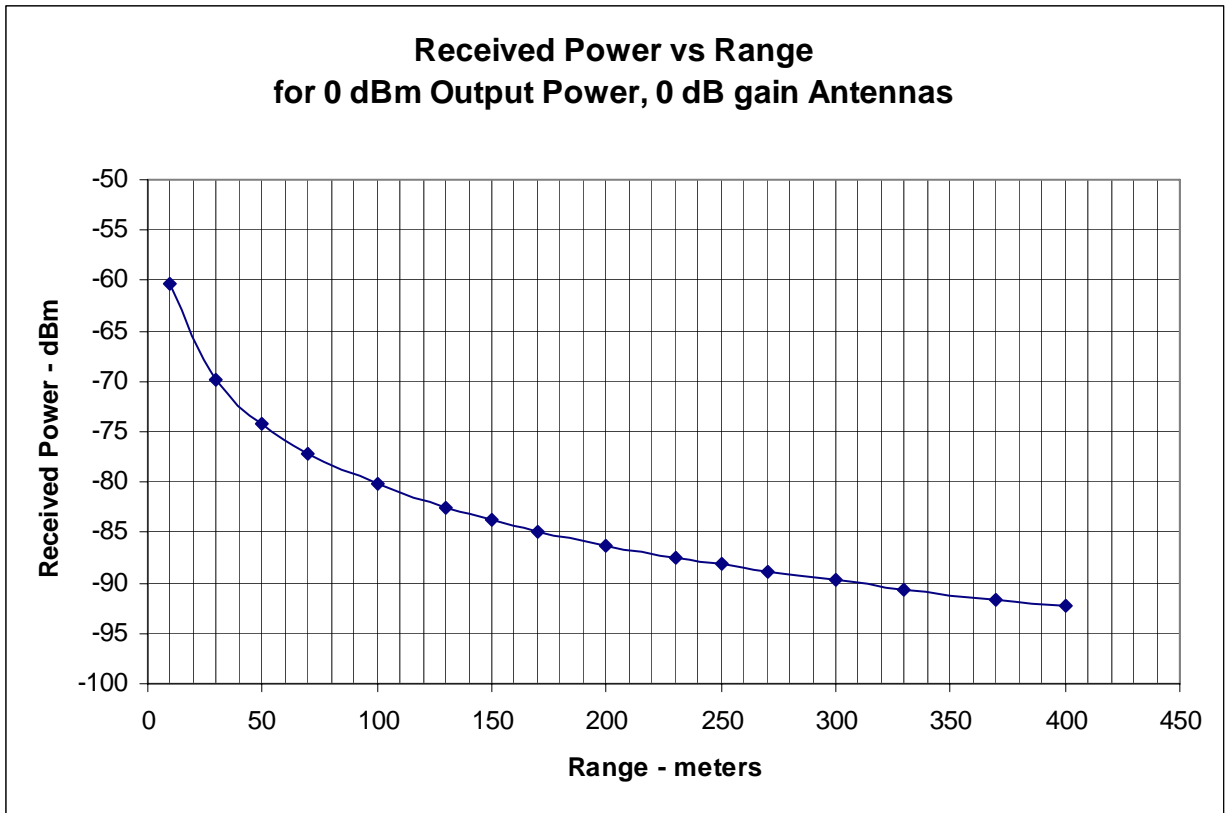
Figure 2-4. Graph of Received Power vs Range

The graph represents a somewhat theoretical best result. Given real losses in the path between the transceiver transmitter and the receiver, real results would typically have greater signal loss.

When doing initial board-to-board testing, with very short distance between transmit and receive modules, LQI may read as high as -60 dBm to -50dBm or higher. Again be reminded, LQI is not very exact and signal strength can vary greatly at very close distance.

2.6.3.2   Antenna Effects

The transmitting antenna characteristics also impact the performance. Different types of antennae will have different gain and different radiation patterns. One inherent problem with very small modules is that as antenna physical size gets smaller it is less efficient.

A good low-cost solution to an 802.15.4 antenna has been a PCB F-antenna that has been a standard on many Freescale designs. The radiation patterns of the F-antenna printed on the 13192-EVB module are shown in Figure 2-5 and Figure 2-6.

- The radiation patterns are for the board orientations (top view) as shown to the right of the polar graph.
- In Figure 2-5 the board is lying flat parallel to a horizontal surface (horizontal pattern)
- in Figure 2-6 the boards is lying on its long side (vertical pattern).

- The measurements were performed with the transceiver set to maximum output power, which results in approximately +2dBm at the antenna plane of the board.

EVK Horizontal PCB Radiation Pattern
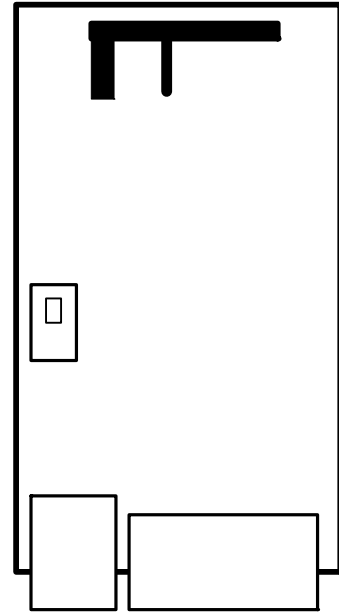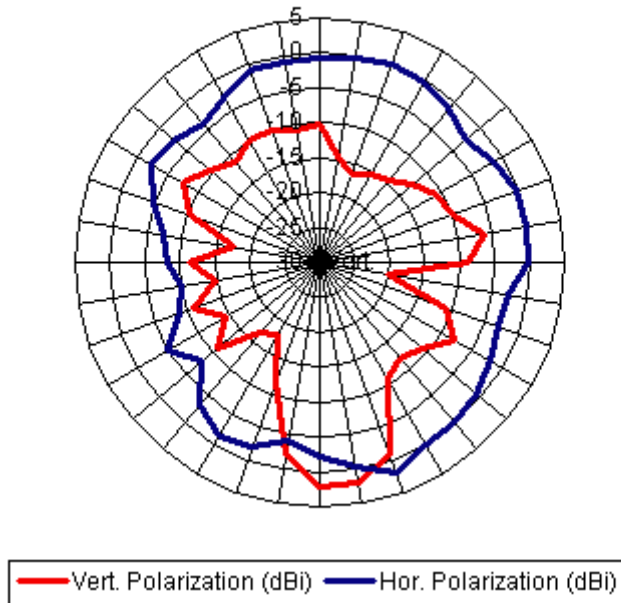
Figure 2-5. 13192-EVB Horizontal PCB Radiation Pattern

EVK Vertical PCB Radiation Pattern
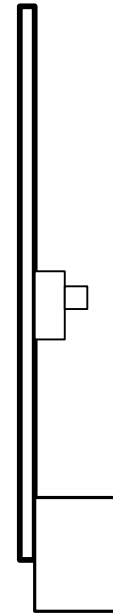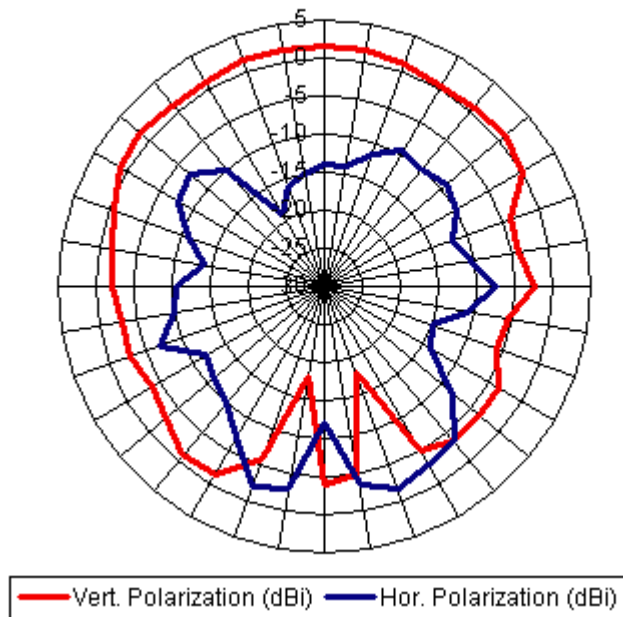
Figure 2-6. 13192-EVB Vertical PCB Radiation Pattern

The radiation patterns show that the F-antenna has best signal strength to either side of the long axis of the antenna. The signal is reduced when perpendicular to the long axis of the F-antenna.

2.6.4   Range Test

Once over-the-air operation of the module is generally validated in a lab situation, some applications may desire evaluation of longer distance via a range test.

Over longer distances, the transmitted wave can produce reflection, diffraction, and/or scattering. Reflection occurs when the transmitted wave encounters an object of large dimension as compared to its wavelength. Common examples are buildings, large walls, and the ground. Some of the energy of the wave may be transmitted or absorbed into the obstruction and the remaining energy will be reflected off of the medium's surface. The energy of the transmitted and reflected waves is a function of the geometry and material properties of the obstruction and the amplitude, phase, and polarization of the incident wave.

Diffraction occurs when the surface of the obstruction has sharp edges producing secondary waves that in effect bend around the obstruction. Like reflection, diffraction is affected by the physical properties of the obstruction and the incident wave characteristics. In situations where the receiver is heavily obstructed, the diffracted waves may have sufficient strength to produce a useful signal.

Scattering occurs when the transmitted wave encounters a large quantity of small dimension objects such as lamp posts, bushes, and trees. The reflected energy in a scattering situation is spread in all directions.

These affect performance in addition to the other factors previously mentioned in Section 2.6.3, "Quantifying PER Test Results".

Although a variety of outdoor environments can be used, Line of Sight (LOS) on level terrain is best to provide a basic understanding of the range performance. Other variables that impact range are:

- Antenna orientation ("standing" or "flat")
- Output power level
- Receiver sensitivity

To implement a range test, it is suggested:

- Both transmitting and receiving boards be positioned about 1.2-2 meters above ground
- It is preferred that both units be connected to a portable laptop PC through a USB cable.
  — Battery operation for the DUT modules is preferred
  — The transmitter can sometimes be used without the PC through use of interface switches.
  — Freescale test software (Section 2.6.2, "Using Freescale Software for Board-to-Board Testing") supports this operation
- Orient the DUT(s) for best antenna performance
- Increase distance until PER performance is unsatisfactory.
- Tests are typically run with nominal 0 dBm, max +2 dBm, and reduced -2 dBm TX power levels

Distances from 80 meters to 1000 meters may be seen depending on antenna type, antenna orientation, and power out.

Range results and path loss calculations are useful in determining link budgets. The link margin is defined as the margin in dB above the receiver sensitivity level required to ensure reliable radio connection between the transmitter and receiver. In optimum conditions (antennas are perfectly aligned, no multi-path or reflections exists, and there are no losses) the necessary link margin would be 0dB. In real world conditions, the link margins are typically in the range of 15 to 25dB.

Chapter 3
FCC Pre-Certification/Certification

3.1 Introduction

The International Telecommunication Union (ITU), a branch of the United Nations, provides guidelines for Radio Frequency (RF) spectrum allocations, but sovereign nations have the right to control radio transmissions within their borders. Certification is the process of testing radio hardware to demonstrate that it meets the stated regulations in the country in which it will operate. With respect to the IEEE 802.15.4 Standard, this discussion addresses intentional radiators, or RF Transmitters, operating in the 2400 MHz "unlicensed" bands.

Generally, when electronic hardware is sold in a country, the certification requirements of that country must be met. Usually only the initial certification is required unless changes are made to the hardware that will affect the RF emission performance. As examples, IC changes and software revisions that do not change radio performance are acceptable (see CFR 47 FCC Part 2.1043). Some countries, like Japan, require filing notification with the regulatory agency even if engineering or demonstrations are performed with RF emitting hardware.

For operation in the 2.4 GHz band (worldwide) the following standards apply:
- In the US, CFR 47 FCC, Part 15.203, 15.205, 15.209 and 15.247
- In Canada, RSS-210 (which closely follows FCC Part 15)
- In the EU, ETSI EN 300, 301
- In Japan, ARIB STD-T66
- Other countries generally follow FCC or ETSI

This chapter provides information and guidance on the pre-certification and certification process.

3.2 Planning for Certification

Start consideration of the certification process early in the design cycle:
- Work with an experienced certification lab to help determine which certification requirements apply to the product
- Perform pre-certification testing or have the certification partner perform the tests to ensure passing before finalizing the design and formally submitting for certification

3.2.1 Choosing the Correct Certification Lab is Important

Freescale recommends consulting an expert. Hire a respected test and certification lab that has experience with unlicensed band hardware and can file (or help file) within the countries of interest.

- Costs will vary from as little as $10K to as much as $20K depending on how many certifications are needed.
- Make sure the certification lab can provide certification in the countries where it is required. Most countries require local filing.
- Select a house with demonstrated expertise in FCC Part 15 hardware certification. Freescale partners include NTS and LS Research.

3.2.2   Include Certification Requirements/Activities in the Design Flow

To avoid issues later in the process, consider certification as part of the design and verification process.

- Select a certification lab BEFORE starting the design.
- Consult with them on critical issues, such as antennas, connectors and labeling. Labeling and Documentation are the primary reason for failure of FCC audits.
- Work close with the lab partner during the design verification phase. Most Labs will gladly provide pre-certification services and advice at a nominal fee.
- Do not wait until a short time before Product Launch to start the pre-certification activities. These should be part of the design cycle. The testing and filing process takes time, in fact it can take as long as 1-3 months.
- Filings must be accepted before the product is shipped

3.2.3   Alternatives

The certification process may present cost and resource barriers to some users. Commercial pre-certified modules are an excellent alternative to OEM design for low volume applications or where RF hardware expertise is lacking. Freescale has module partners. FCC and other regulatory agencies allow for "modular" certification where the OEM can use a certified module and does not have to re-certify.

NOTE

An exception is if the radio transmitters are within 20 cm of each other, the hardware must be re-certified.

3.2.4   Suggested Reading / References

Some suggested sources of additional information:

- CFR 47 FCC Part 15 – available from the FCC web site. Sections 35, 205, 209, 247
- FCC Publication 558074 – gives details on measuring digital radios; available from the FCC web site (use Google search)
- "Simplifying FCC Compliance for 802.15.4 2.4 GHz Devices" – White paper by Glen Moore, Wireless/EMC Manager, National Technical Systems

3.3 Pre-Certification Testing

Basic RF test and verification have already been detailed. Once the design is working, there are some basic measurements that should be made prior to Certification Testing. Consider these two options:

- Work with the Certification Lab on the first hardware design and have them assist as to how to make these measurements
- Considering the complexity of the measurements, contract a Certification Lab to perform these tests

NOTE

- FCC Publication 558074 provides more details on measuring digital radios
- These tests may measure a similar parameter by different means than described in Chapter 2, "RF Design Validation and Verification".

Tests are performed in Continuous Modulation transmission mode (not packet) or PRBS9 random data packet mode

A summary of pre-certification tests includes:

- Peak Output Power - conducted and radiated
- Spurious Emissions - conducted
- Spurious Emissions - radiated
- Duty Cycle Correction Factor
- Power Spectral Density (NOT as defined in IEEE 802.15.4 Standard)

NOTE

The listed pre-certification tests do not cover all the required certification tests, but rather focus on the RF attributes that are impacted by the customer board design. Since the tests are more easily done in conducted mode and conducted mode gives more consistent results, Freescale recommends performing all of the pre-certification tests in this mode and doing an approximate mathematical conversion to determine specification compliance.

Freescale provides applications for these tests, and continuous transmit modes are available in Freescale SMAC test software (Test Mode application and Connectivity Test). The transmit mode suitable to a related test is as follows:

- Duty Cycle Correction Factor measurement uses PRBS9 mode
- Power Spectral Density measurement uses PRBS9 mode
- Spurious measurements uses Continuous Modulated mode
- Peak Power measurements uses Continuous Modulated mode

3.3.1   Measurement Equipment

The instrument list for the transmitter tests is shown in Table 3-1. In addition, other equipment such as amplifiers, attenuators, filters, etc. are needed.

Table 3-1. Equipment Required for Transmitter Tests

Test Parameter	Spectrum Analyzer	Vector Signal Analyzer
6dB Bandwidth	1	
Occupied Bandwidth	1	
Peak Power	1	
Power Spectral Density	1	
Duty Cycle Correction Factor	1	
Conducted Spurious Emissions	1	
Conducted Spurious Emissions Band Edge	1	
Radiated Spurious Emissions	1	
Equivalent Isotrophic Radiated Power	1	
Maximum E.I.R.P. Spectral Power Density	1	
Frequency Range	1	
Transmitter Spurious Emissions	1	
Receiver Spurious Emissions	1	

3.3.2   Peak Output Power

Peak output power is the maximum TX power at which the unit will operate. FCC Part 15.247 (b) (3) applies:

* Sets a limit of 30 dBm
* This limit applies to conducted or radiated measurements. See FCC regulations for more detail regarding radiated requirements
* Making the test as an RF conducted test is the easiest method to verify. Most applications operate at a level that is far less power than the FCC limit.. Use a direct connection between the antenna port of the transmitter and the spectrum analyzer, through suitable attenuation
* Sets the spectrum analyzer resolution bandwidth (RBW) greater than 6 dB bandwidth of the emission, or use a peak power meter

3.3.2.1   Test Conditions

* 10 MHz RBW and video bandwidth VBW
* Peak Detector
* Max hold
* NOT a band power measurement

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- Test at low (band edge), mid and high (band edge) channels, i.e., frequencies 2405, 2445, and 2480 MHz
- Use continuous modulated transmit mode (not packet)

Use a spectrum analyzer and perform the following tasks:

1. Set the SA center frequency to test frequency.
2. Set the power to max power.
3. Set the Resolution Bandwidth to 10 MHz.
4. Set the Video Bandwidth to 10 MHz.
5. Set the Span to 20 MHz.
6. Set the sweep time to auto.
7. Set the Spectrum Analyzer Detector mode to Peak Detector.
8. Set the Normal Marker to the peak magnitude.
9. Record the Peak Power.
10. Repeat listed steps for all remaining frequencies.
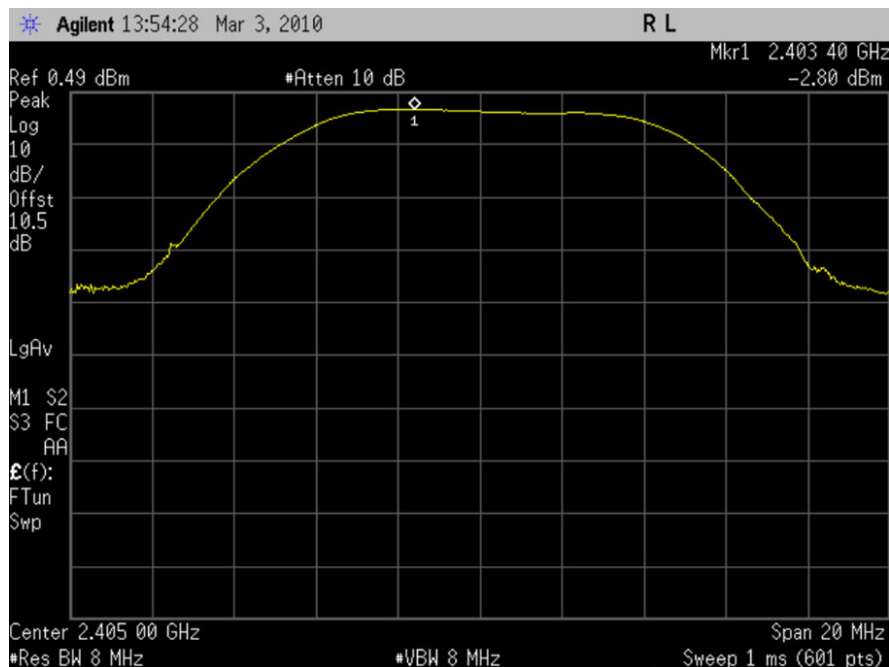
Figure 3-1. Peak Output Power

3.3.3   Spurious Emissions - Conducted (basic)

Spurious emissions are the unwanted transmit spectrum including harmonics, spurs and spectral mask. The FCC Part 15.247 (d) applies:

- Sets a limit of -20 dBc for peak power or -30 dBc for average power within a 100 kHz bandwidth

NOTE

RMS average power has a very specific definition as used in the FCC
document. Be cautious when applying this method.

- Sets the test as an RF conducted <u>and radiated</u> tests. This section applies to conducted test.
- Sets the spectrum analyzer resolution bandwidth (RBW) to 100kHz

The FCC also requires a conducted spurious emissions test more specific to the band edges (see
Section 3.3.4, "Conducted Spurious Emissions Band Edge").

3.3.3.1   Test Conditions

- 100 kHz RBW, 300 kHz VBW
- Peak Detector
- Auto Sweep with Max Hold
- Test each test frequency with Full spectrum sweep and band edge for each useable power level at low, mid, and high-band transmission frequencies, i.e., 2405 MHz, 2445 MHz, and 2480 MHz.
- Use continuous modulated transmit mode (not packet)

Use a spectrum analyzer and perform the following tasks:

1. Set the DUT Low frequency to be tested.
2. Set the DUT power to desired power.
3. Set the SA Start Frequency to 30 MHz.
4. Set the Stop Frequency to 26 GHz (or SA maximum frequency if less than 26 GHz).
5. Set the Resolution Bandwidth to 100 KHz.
6. Set the Video Bandwidth to 300 KHz.
7. Set the sweep time to 52 s.
8. Set the detection mode to Peak.
9. Must meet 20 dBc Peak or 30 dBc Average (See FCC document for definition of average.)
10. Repeat for each remaining frequency and power that the device will be operated.
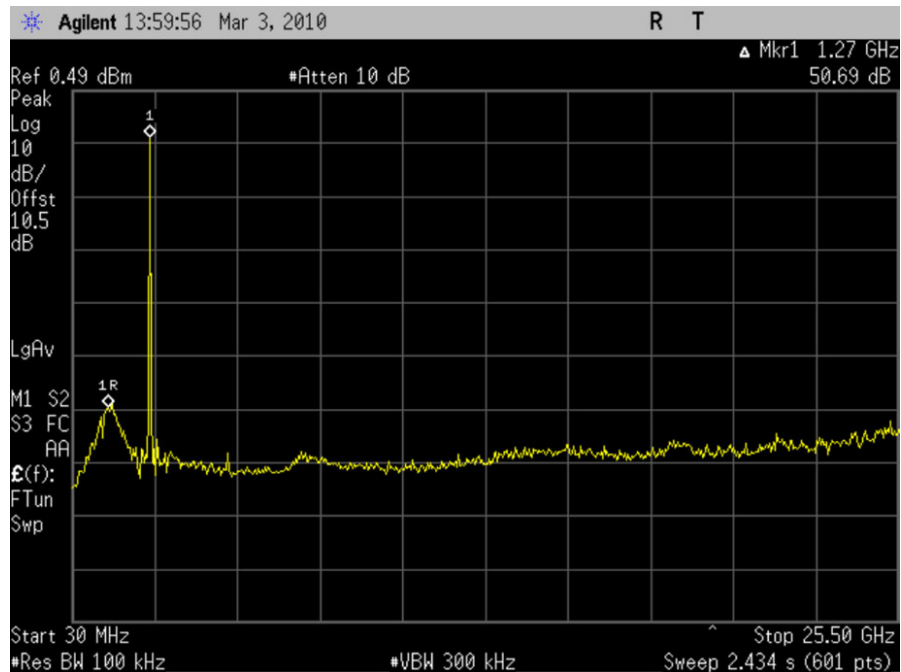
Figure 3-2. Conducted Spurious Emissions (basic)

3.3.4   Conducted Spurious Emissions Band Edge

The conducted spurious emissions band edge tests are in addition to the basic spurious emissions test. The conducted spurious emissions are determined for low-band and high-band transmission frequencies, i.e., 2405 MHz, and 2480 MHz. On either side of the 802.15.4 band are forbidden bands. Therefore, this close look is necessary for compliance assurance. When using an external PA, the highest useable transmission frequency is 2475 MHz.

Use a spectrum analyzer and perform the following tasks:

1. Set the DUT Low frequency to be tested.
2. Set the DUT power to desired test power.
3. Set the SA Center Frequency to 2400 MHz.
4. Set Span to 20 MHz or wider if necessary to capture possible spurious peaks.
5. Set Resolution Bandwidth to 100 KHz.
6. Set Video Bandwidth to 300 KHz.
7. Set sweep time to 5 ms.
8. Set detection mode to Peak.
9. Set display to Max Hold.
10. Locate highest in-band peak and highest peak below 2400 MHz - must meet 20 dBc Peak or 30 dBc Average.
11. Repeat for each remaining frequency and test power.
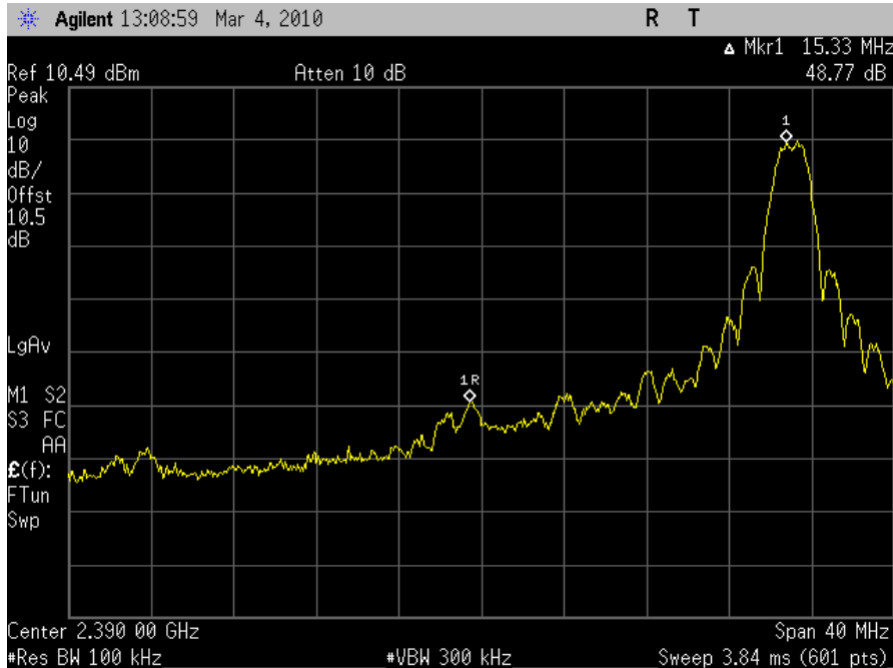
Figure 3-3. Conducted Spurious Emissions Low-Band Edge

For high-band edge, repeat the above measurements with Center Frequency set to 2.4835 GHz for Step 3. Look for highest peak above 2.4835 GHz in Step 10.

3.3.5   Spurious Emissions - Radiated (basic)

Spurious emissions tests done with the radiated RF signal are also required and are similar to conducted tests, but are done in a 3-meter RF chamber. The FCC Part 15.247 (c) applies as well as Parts 15.209 and 15.205 because the ISM 2.4 GHz band has "forbidden bands" on either side of it (these bands include 2.2 - 2.3 GHz, 2.31 - 2.39 GHz, and 2.483 - 2.5 GHz). The set limit is 500μV/m (54 dBμV/m) for the average detector.

Most users do not have the specialized equipment necessary to make radiated measurements, so conducted measurements with antenna gain can be substituted for gauging FCC compliance. Table 3-2 shows the signal power conversions necessary for using conducted tests.

The above limit of 500 uV/m @ 3 meters in FCC 15.209 is converted to dBuV/m as follows:

- $20 * \log(500) = 53.98$ dBuV/m
- The peak limit is 20 dB above 53.98 or 73.98 dBuV/m

Table 3-2. Power Conversions for Limits When Substituting Conducted Tests for Radiated Emissions

Frequency Range of Harmonic or Spurious Emission (MHz)	Average Limit Converted from Field Strength to dBm Measured @ RF Port (dBm)	Average Field Strength Limit of Fundamental @ 3m (dBμV/m)	Peak Field Strength Limit of Fundamental @ 3m (dBμV/m)	Peak Limit Converted from Field Strength to dBm measured @ RF Port (dBm)
Above 960	-41.12	54	74	-21.2

NOTE

Refer to the National Technical Systems "white paper" cited in
Section 3.2.4, "Suggested Reading / References" for more information.

A test method is presented here to achieve a level of confidence in equivalent radiated data from conducted measurements.

3.3.5.1 Test Conditions

- FCC Publication 558074 specifies Continuous Modulation mode, not packet mode
- If the Average limit is applied, a Duty Cycle Correction Factor (DCCF) can be used per 15.35 (b):
  — On-time / Off-time in 100 ms
  — DCCF can only be applied to the fundamental related spurious and not random spurious.
  — The IEEE 802.15.4 standard is a burst-mode, low duty cycle protocol with a relatively low raw bit rate of 250 kbps. The DCCF can be generally estimated by use model; experience has shown that an equivalent throughput of ~75 kbps (30% duty cycle) is a very high usage model, and in contrast, the ZigBee Alliance specifies no more than 10% duty cycle. A reasonable compromise is a common packet model: one full packet transmitted with no acknowledgement received, then the packet is re-transmitted 3 more times with no acknowledgement, yielding a 17% duty cycle:
    – Maximum 802.15.4 packet contains 133 bytes
    – At 250 kbps data rate, bit time = 4 µs and byte time = 32 µs
    – 133 byte packet lasts 4.26 ms.
    – 4 transmitted packets is total on-time of 17 ms
- Using averaging measurement
  — 1 MHz RBW, 10 Hz VBW
  — Auto Sweep with Max Hold
  — Continuously modulated
  — Apply duty cycle correction factor (DCCF)
- Alternatively, Peak limits and conditions can be used. The Peak limit can be applied with no correction factor.
  — 1 MHz RBW, 1MHz VBW
  — Auto Sweep with Max Hold
  — Continuously modulated
  — Do Not Apply duty cycle correction factor (DCCF)
- The Spurious Emissions are determined for low-band and high-band transmission frequencies, i.e., 2405 MHz, and 2480 MHz. When using an external PA, the highest useable transmission frequency is 2475 MHz.

NOTE

Do not use dBµV mode on the spectrum analyzer; it does not correct for radiated power.

802.15.4/ZigBee RF Evaluation and Test Reference Manual, Rev. 1.0

Use a spectrum analyzer and perform the following tasks:

- Follow the method as described in Section 3.3.3, "Spurious Emissions - Conducted (basic)" by doing a general spur search, breaking up the span above and below the intentional radiator as needed to detect spurs with the detector in peak mode above the desired frequency band. Set the detector to quasi-peak CISPR for frequencies below 1GHz.

- The frequencies covered should go from below the band edge down to as close to DC as possible and above the band edge to 26 GHz (or as high as your equipment will allow).

1. Set the DUT Low frequency to be tested.

2. Set the DUT power to desired test power.

3. Set Start Frequency to 30 MHz (The blocking caps in the SA does not allow it to be in calibration below approximately 30 MHz).

4. Set Stop Frequency to 2.39 GHz.

5. Set Resolution Bandwidth to 1 MHz.

6. Set Video Bandwidth to 10 Hz (averaging measurements).

7. Set sweep time to 60 s.

8. Set detection mode to Peak.

9. Set display to Max Hold.

10. Locate highest peak and place a marker-normal.

11. Note Frequency and magnitude. Spurs must meet -21.2 dBm peak (VBW=1 MHz) and -41.2 dBm average (VBW=10 Hz).

12. Repeat Steps 2 through 11 for High band frequencies and operating powers.

When performing the conducted tests for qualification of radiated results, the measurements need to be converted to dBuV/m and compared to these limits. To convert conducted measurements into radiated @ 3 meters:

- Subtract 95.2 from the measured conducted spur to obtain dBuV/m from dBm

- The RMS detector measurements (VBW= 10 Hz) are then reduced by the DCCF before being compared to the 53.98 limit

- The peak detector measurements are compared to the 73.98 limit

- Note that the DCCF is not applied to the peak limit (VBW= 1 MHz)

NOTE

If pulsed measurements are the only method of measuring the signal, then be sure to synchronize the SA to the output signal. Otherwise, the video effects of how the SA interprets the signal will give false data which could cause the part to seem to fail the limits. If the DUT cannot be put into continuous mode, this fact needs to be communicated to your certification vendor.
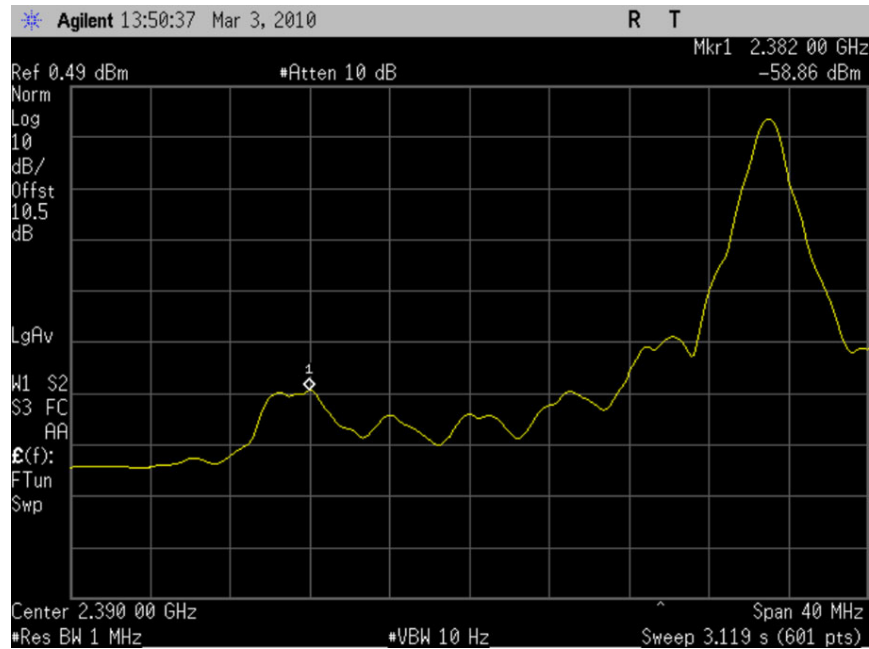
Figure 3-4. Radiated Spurious Emissions (Measured Conducted - Video Average)
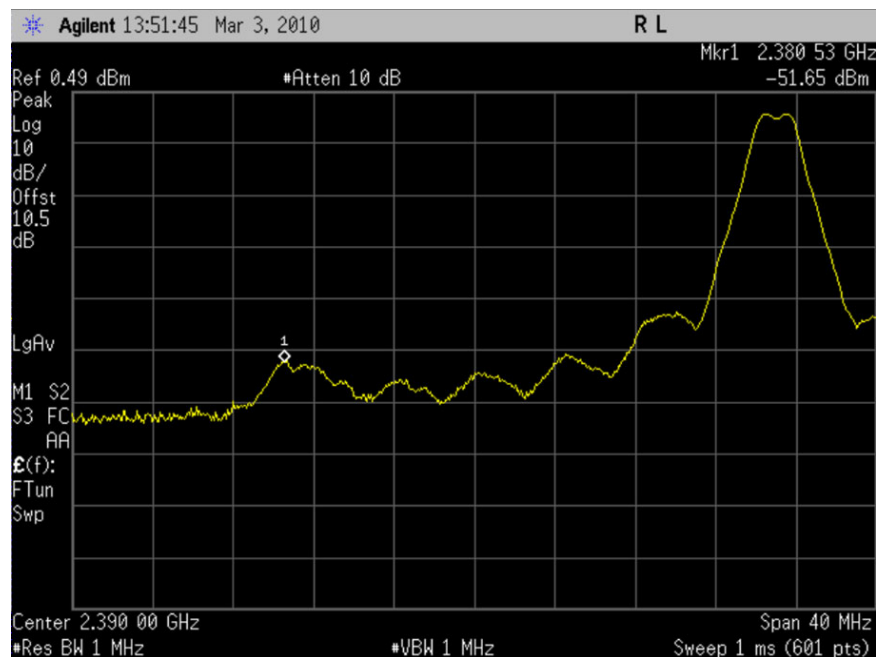
Figure 3-5. Radiated Spurious Emissions (Measured Conducted - Video Peak)

3.3.6   Radiated Spurious Emissions Band Edge

The radiated spurious emissions band edge tests are in addition to the basic radiated spurious emissions test. Again, actual conducted tests are used to quantify the radiated performance.

The conducted spurious band edge emissions are determined for low-band and high-band transmission frequencies, i.e., 2405 MHz, and 2480 MHz. When using an external PA, the highest useable transmission frequency is 2475 MHz.

Use a spectrum analyzer and perform the following tasks. Peak detection is found first, then the average detection.

1. Set the DUT Low frequency to be tested.
2. Set the DUT power to desired power.
3. Set the Spectrum Analyzer Center Frequency to 2390 MHz.
4. Set Span to 40 MHz.
5. Set Resolution Bandwidth to 1 MHz.
6. Set Video Bandwidth to 1 MHz.
7. Set sweep time to 5 ms.
8. Set detection mode to Peak.
9. Set display to Max Hold.
10. Locate highest peak below 2390 MHz - Must meet 73.98 dBuV/m Peak.
11. Repeat for each remaining frequency.
12. For average detection, repeat above steps Step 1 - Step5, then make the following SA settings changes, and finally measurement Step 10:
    — Step 6. Set Video Bandwidth to 10 Hz
    — Step 7. Set sweep time to 10 s

NOTE

> The equipment may be unable to achieve the combination of 10 s sweep and 10 Hz VBW. Freescale recommends that the span be adjusted to accommodate the VBW as necessary.

    — Step 8. Set display to Clear Write
    — Step 10. Locate highest peak below 2390 MHz - must meet 73.98 dBuV/m Peak (VBW= 1 MHz) and 53.98 dBuV/m Average (VBW= 10 Hz)

For high-band edge, repeat above measurements with Center Frequency set to 2.4835 GHz for Step 3. Look for highest peak above 2.4835 GHz in Step 10.

The limit of 500 uV/m at 3 meters in FCC 15.209 is converted to dBuV/m as follows:

20 * log(500)=53.98 dBuV/m. The peak limit is 20 dB above 53.98 or 73.98 dBuV/m.

The above measurements need to be converted to dBuV/m and compared to these limits.

To convert conducted measurements into radiated at 3 meters, subtract 95.2 from the measured conducted spur to obtain dBuV/m from dBm. The RMS detector measurements are then reduced by the DCCF before being compared to the 53.98 limit. The peak detector measurements are compared to the 73.98 limit. Note that the DCCF is not applied to the peak limit. Also, do not apply the DCCF to spurious that is not related to the fundamental.

3.3.7 Duty Cycle Correction Factor

If used, the FCC certification process requires that the stated DCCF for the module be demonstrated. The duty cycle of the transmitter is observed with a 100ms window.

3.3.7.1 Test Conditions

- PBRS9 transmit mode is used with your application duty cycle
- Use SA in zero span
- Measure on-time versus off-time in 100 ms
- Use mid-band frequency (2445 MHz)

Use a spectrum analyzer and perform the following tasks

1. Set the DUT center frequency to be tested.
2. Set the DUT power to max power.
3. Set the SA SPAN to ZERO SPAN.
4. Set Resolution Bandwidth to 10 MHz.
5. Set Video Bandwidth to 10 MHz.
6. Set Span to 20 MHz.
7. Set the SA sweep time to 5 ms.
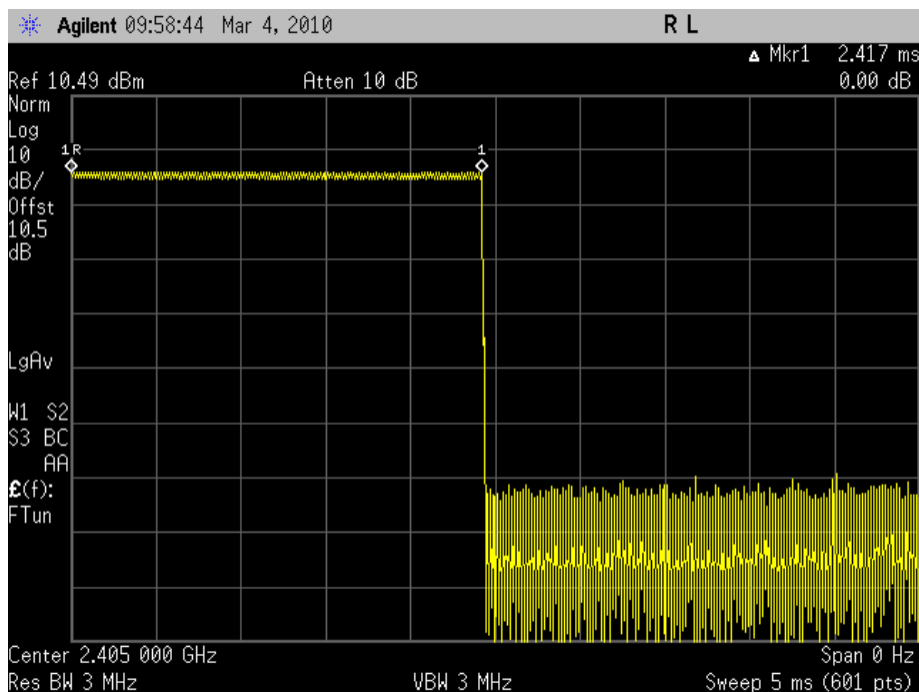
Figure 3-6. On Time for a Single Pulse

802.15.4/ZigBee RF Evaluation and Test Reference Manual, Rev. 1.0
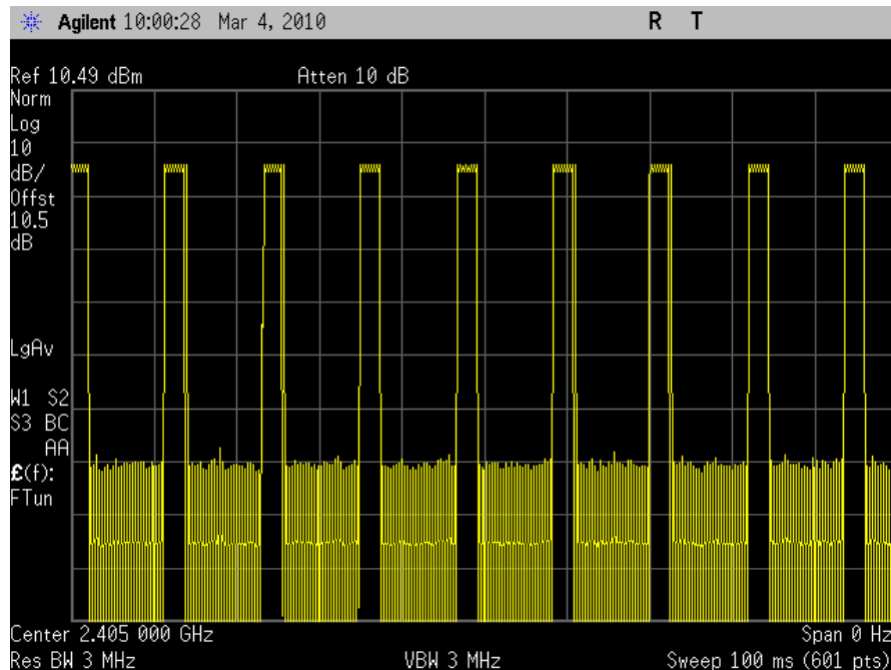
Figure 3-7. Number of Pulses During 100ms Duty Cycle

In this case, the ON-Time is 2.417 mS. Since there are 9 pulses in 100 mS, the duty cycle is (9*2.417)/100. The Duty Cycle Correction Factor (DCCF) is then 20 Log (Duty Cycle)= 10 Log (.2175) = -6.62 dB. This means that the radiated average data can be de-rated by 6.62 dB before being compared to the FCC requirement.

3.3.8   Power Spectral Density (PSD)

Power Spectral Density may also be observed as part of pre-certification, but is not necessarily required as it is determined by modem's transmitter. FCC Part 15.247 (d) applies:

- Sets a limit of 8 dBm / 3 kHz
- Sets the test as an RF conducted test

3.3.8.1   Test Conditions

- 3 kHz RBW and VBW > RBW
- Peak Detector
- Max hold
- Sweep = 500 seconds (Span/3 kHz)
- Span = 1.5 MHz
- Test at low (band edge), mid and high (band edge) channels, i.e., frequencies 2405, 2445, and 2480 MHz
- MUST use PRBS9 transmit mode

NOTE

This measurement is strictly a conducted value as the FCC specifies the power spectral density delivered to the antenna.

Using a spectrum analyzer (SA), a suggested procedure is:

1. Set the SA center frequency to the desired frequency to be tested
2. Set the DUT power to max power
3. Set the Resolution Bandwidth to 3 KHz
4. Set the Video Bandwidth to 10 KHz
5. Set the Span to 1.5 MHz
6. Set the sweep time to 500 s
7. Set the detector mode to Peak Detector
8. Set the Normal Marker to the peak magnitude
9. Record the Peak Power - compare against the 8 dBm max requirement.
10. Repeat steps listed above for remaining frequencies
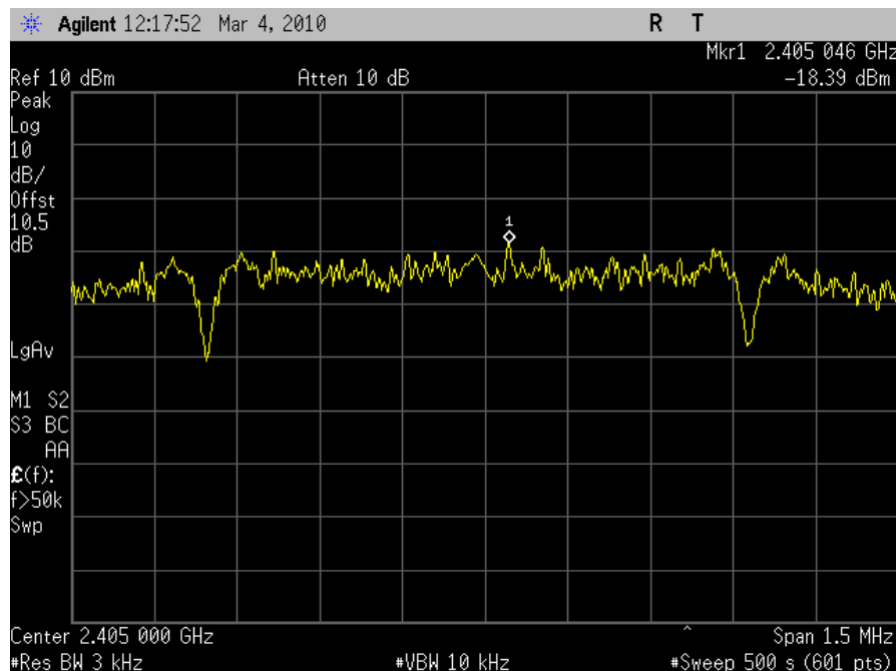
Figure 3-8. Power Spectral Density

3.4   Getting Certification

This set of tests are inclusive but not comprehensive of those required to pass FCC certification. Once product development and pre-certification testing is complete, the actual certification is done in partnership with the Test and Certification Lab. If an early relationship has been developed, this process should go smoothly. The certification testing will require certain deliverables by the assembly vendor, and these may include:

- Specific target hardware ready for conducted tests
- Specific target hardware ready for radiated tests.
- Special applications or utilities for testing
  — Test suites to facilitate certification tests
  — End-to-end application(s) for interference tests
- Supporting documentation (IC data sheets, schematics, bill of materials, etc.)

The test lab will be able to give guidance on the required support package for a particular certification.

Chapter 4
Production Test Guidelines

4.1   Introduction

This chapter describes manufacturing test recommendations for products that employ Freescale IEEE®
802.15.4 Standard wireless technology. This information is intended for test, system, and product
engineers responsible for developing and maintaining production test systems for these products. It is
recommended that they are familiar with the IEEE 802.15.4 Standard and its associated terminology, and
also have a basic working knowledge of board test techniques.

NOTE
- This chapter is not intended as a full test suite guide and assumes the
  user is familiar with manufacturing test methodologies. This chapter
  provides guidance to specific requirements that may be unique or useful
  to the Freescale IEEE 802.15.4 devices and applications.
- A number of vendors supply commercial test tools and equipment
  specifically targeted for IEEE 802.15.4 / ZigBee applications. The user
  is encouraged to investigate these solutions as they may provide
  significant benefits.

4.2   Production Test Characteristics

The board or module that is the Device Under Test (DUT) will already have been evaluated and validated
by earlier design and test stages. As a result, the production test stage of the development cycle focuses on
reducing test time and lowering manufacturing costs per unit while still validating that the units leaving
the production line are properly assembled and functional. The production test process must encompass
the following elements:

- Repeatability
- Stability
- Robustness
- Reliability
- Cost Effectiveness

Consider several important test steps on the manufacturing floor when dealing with IEEE 802.1.5.4
Standard chipsets:

- Programming an application image
  - A test application image into MCU RAM or non-volatile memory (NVM)
  - Final target application NVM image

- Communication interface
- RF Tests
- Crystal Test and Calibration
- MAC Address Handling
- Software Tools

4.3   Freescale Tools to Support Production Test

In the following descriptions, it is stated that a test application can run on the target MCU to assist in production test. Freescale provides test software tools/utilities and a number of application notes that can assist developing tools for production test applications.

- See Appendix A, "Freescale 802.15.4 RF Test Software" for a listing of software utilities and associated application notes. The primary software utilities useful to production testing are -

    The ZigBee Test Client (ZTC) — This is a MAC based application.

    Connectivity Test — This is a SMAC based application.
- AN3860 - *MC1322x Flash Loader Utility (Second Stage Loader)*

4.4   Programming a Test Application or NVM Image

The Freescale portfolio of parts for the IEEE 802.15.4 Standard includes 8-bit (HCS08) and 32-bit (ARM7 based) MCUs and several different memory configurations. This requires numerous options for programming the DUT in the production line. Also, two different types of images may be required to be loaded:

Test application image   To functionally validate the transceiver/radio and any peripheral functions, an application can be loaded that enables/performs prescribed tests. Depending on the target device, the test application can reside in RAM or in NVM (FLASH memory).

Final target application The end application binary image must be loaded into the MCU NVM. This can happen as part of the final production test flow or it can be pre-loaded prior to board assembly using commercial solutions

Depending on production volume, it is usually more convenient to have the ICs programmed prior to the assembly process.

For low to medium volume programming, tools are available from various Freescale tool vendors for on-board programming. For the 8-bit products, P&E Micro offers the Cyclone Pro USB Multilink[©] interface. For the 32-bit products, IAR offers software to work with the J-Link[©] ARM Processor programmer. For high volume programming, tooling is available for all products from System General and programming services are available from Source Electronics, which is now part of Avnet.

4.4.1   HCS08 Platforms

All the HCS08 MCUs feature in-circuit debug and FLASH programming tools available via the on-chip background debug module (BDM) and its serial debug port. Although this is the common, primary means

of downloading a target application image, there is also the option of using a serial UART port in conjunction with a test application. These are described as follows:

- BDM debug serial port -
    - Access to the BDM port is most commonly supplied via a standardized 2x3 6-pin header compatible with the P&E Micro (www.pemicro.com) USB CYCLONE PRO tool for HCS08.
        - The MCU BKGD and RESET lines must be available for this connection
        - Alternatively, access to this port has been provided via PCB pads for a bed-of-nails connection. These test signals can be routed to the BDM tool.
    - If the HCS08 FLASH has been pre-programmed with the target application in NVM, a test application would normally execute from RAM. This limits the test application binary size to the RAM size which is typically from 4 kbytes to 8 kbytes.

NOTE
The target application can include a means to load and the run test code in RAM or the BDM can be used to load the test code (although this must be done carefully)

-
    - Commercial solutions, such as those provided by P&E Micro can be employed to program the HCS08 based MCU in the production line.
- Test application and communication port - Freescale provides a MAC-based application called Test Tool. Test Tool consists of a target MCU client application and a personal computer (PC) Command Console application to communicate with and control the MCU client application through a UART port. The Test Tool client can be loaded via the BDM port, and then run as a test application.
    - For production test purposes, the Command Console application must be replaced by a test interface such as a NI LabVIEW™ application.
    - Test Tool PC application supports loading of a FLASH application image through the BDM.

4.4.2   ARM7 Platforms

The ARM7 solutions from Freescale are different from the HCS08 platforms in that an application program executes from ROM/RAM as opposed to executing directly from FLASH as on the HCS08 platforms. In normal operation, the boot process for these devices executes from ROM, transfers a binary image from serial FLASH to RAM and then transfers execute to RAM. This provides a different model than the HCS08 for loading a program image and for loading test code. Two different programming options for the ARM7 platform include the serial debug interface and alternative boot load approach:

- Serial debug port
    - The ARM7 debug serial interface is via a standardized JTAG debug port - this port is used for in-circuit debug and serial FLASH and/or RAM programming. Access to the JTAG port is most commonly supplied via a standardized 2x10 20-pin header compatible with the IAR Systems (www.iar.com) J-Link USB-JTAG Debugger for ARM.
        - The MCU TDI, TMS, TCK, RTCK, TDO and RESET lines must be available

- – Alternatively, access to this port can be provided via PCB pads for a bed-of-nails connection. These test signals are then routed to the J-Link tool.
- — A test application can be loaded and executed from RAM, and the test application binary size can be as large as 80 kbytes.
- — Commercial solutions, such as those provided by IAR, can be employed to program the serial FLASH in the production line.

- Similar to the HCS08 scenario, the Freescale Test Tool MCU client can be loaded into RAM of the ARM7 platform. The client has a NVM load utility.

- Boot load option - The ARM7 platform boot process involves first executing from ROM and normally loading the RAM from a valid serial FLASH image. If no valid FLASH image is present, the alternate boot flow can used to load an executable.

NOTE

- If the ARM7-based device has had a valid application image loaded into the serial NVM prior to board assembly, the boot load option for production is not possible. The standard JTAG debug port tools must be used.
- Although the alternate boot load option is briefly described here, the user is directed to the *MC1322x Reference Manual* (MC1322xRM), Chapter 3 and Appendix C for complete information on the device bootloader

- — Lacking a valid NVM image, the ARM7 boot flow looks for an alternate source of executable code from a prioritized set of serial interface ports. The user can enable UART1 (most common), the SPI port, or the I^2C bus as the boot load port
  - – For the selected port, the corresponding interface signals must be available with no conflict with external peripherals
  - – The selected option must be enabled as described in the *MC1322x Reference Manual*, (bootstrap flow)
  - – The communication protocol and data formatting are described in the *MC1322x Reference Manual*
- — Freescale provides software utilities to help implement this process
  - – The Test Tool suite is available in the Freescale BeeKit Wireless Connectivity Toolkit.
  - – Application note AN3860, *MC1322x Flash Loader Utility (Second Stage Loader)* is also useful

4.4.3   Updating or Reloading of NVM Image

Although not necessarily part of the production test flow, the need for updating/reloading a valid application image in NVM may be required after production or in the field.

- Providing a PCB onboard connector for the device serial debug port as a standard feature is good practice. This enables use of the debugger hardware in the field for both debug and updating the NVM image.

- The RF communication capability of these modules provides a unique potential option of over-the-air programming (OTAP) to update the NVM image. This is costly in that an external serial NVM must be present to store the new image as it is received by the target node for later self update. Freescale provides sample applications that demonstrate this function.
- Described in Section 4.4.2, "ARM7 Platforms", the boot load option can be also used for field update of these platforms. One caution is that the present valid NVM image must first be erased before the boot load function can be used, and hardware means can be provided to facilitate self-erase of the NVM image. See the *MC1322x Reference Manual*.

4.5 Communication Between Tester Platform and DUT

The primary communication channel between the tester and the DUT is normally the MCU serial debug port. The appropriate debugger tool connects to the DUT, and in turn, communicates back to a personal computer (PC) typically through a USB port. Debug/Test/NVM utility software runs on the PC and supports the test environment.

It is also common practice to take advantage of the onboard MCU to test the radio and any utilized peripherals. The test application can run out of RAM and can be downloaded through the serial debug port. A disadvantage after the test application is downloaded and running is that communication through the debugger can be fairly slow and can lengthen test time.

A good option is to dedicate a serial port such as a UART to tester communication.

- Communication rate will be much faster than using the serial debugger
- The target test application must support the communication interface
- The communication interface signals must be available to the tester as a connector or as pads on the PCB
- A commons means is to use a DUT UART
  - Provide an off-board UART<>USB interface, and the PC can support the USB connection as a Virtual Comm Port (VCP)
  - This channel can also be used for the ARM7 platform boot load interface if desired.
- This can provide a direct control channel for sending commands to the target test application

4.6 Crystal Testing and Calibration

In many other MCU applications it is sufficient to know that a crystal frequency source is running, and the actual frequency error (as determined by the crystal and its loading) is not critical. However, as described earlier, the IEEE 802.15.4 Standard requires that the frequencies and symbol rates associated with the radio transmit and receive functions have an accuracy of +/-40 ppm or better.

- With properly specified crystals, Freescale devices can maintain a typical accuracy of +/-30ppm or better over temperature and voltage variation.
- The recommended crystal specifications list a maximum frequency cut of $\pm$ 10 ppm at 25 °C
- It is recommended that the DUT frequency error be tested and assured that it is $\pm$ 10 ppm or less; if not, individual unit tuning may be required. The Freescale IEEE 802.15.4 ICs can all trim the crystal reference oscillator frequency through programming of onboard trim load capacitance.

4.6.1 HCS08 Platforms

The MC1320x and MC1321x devices have a 16 MHz reference oscillator that is part of the transceiver IC and are trimmed by writing to a SPI register on the transceiver. All Freescale software for these devices is based on the HCS08 platform. Guidelines for measuring the error frequency include:

- Monitor the reference frequency at output pin CLKO
  - — Do not load the crystal oscillator pins directly because this causes a frequency shift.
  - — The CLKO signal must be available for test
- Use an accurate frequency counter (resolution of 1-2ppm) such as an Agilent 53131A
- A test application running on the target MCU should support changing the trim setting in the proper transceiver SPI register (Register 0A Bits 15-8 xtal_trim [7:0]) - the production test equipment should include an automatic routine to trim the frequency in the production line based on the frequency counter reading. A good target at room temp is $> \pm 10$ ppm.
- The custom trim value is retained to be inserted into the target MCU application code image.

A custom oscillator trim value can be one of multiple custom parameters that need programmed into the DUT NVM. See Section 4.8.1, "HCS08 Parameters" for a description of programming techniques.

NOTE

For HCS08 FSL MAC-based applications, the crystal trim parameter is **Abel_HF_Calibration**. See Section 4.8.1, "HCS08 Parameters" for a description of programming techniques..

4.6.2 ARM7 Platforms

The MC1322x devices have a single IC for the radio/MCU combination and the 24 MHz (typical) reference oscillator is onboard and trimmed by writing a register in the MCU register address map. Guidelines for measuring the error frequency include:

- The MC1322x devices do not have a clock-out pin, a timer module (TMR) must be programmed as a divider and the resulting frequency out monitored at the TMRx's associated at output pin TMRx. Similar to the HCS08 guidelines -
  - — Do not load the crystal oscillator pins directly because this causes a frequency shift.
  - — The TMRx signal must be available for test
- Use an accurate frequency counter (resolution of 1-2ppm) such as an Agilent 53131A
- A test application running on the target MCU should support changing the trim setting in the proper control register (XTAL_CNTL Bits 25-16, {XTAL_CTUNE[4:0],XTAL_FTUNE[4:0]}) - the production test equipment should include an automatic routine to trim the frequency in the production line based on the frequency counter reading. A good target at room temp is $> \pm 10$ ppm.
- The custom trim value is retained to be inserted into the target MCU application code image.

A custom oscillator trim value can be one of multiple custom parameters that need programmed into the DUT NVM. See Section 4.8.2, "ARM7 (MC1322x) Parameters" for a description of programming techniques.

NOTE

For ARM7 MAC-based applications, the crystal trim parameters are
gXtalCTune_c and **gXtalFTune_c**. See Section 4.8.2, "ARM7 (MC1322x)
Parameters".

4.7   RF Tests

As already stated, the main goal of production test is to validate that the DUT is assembled correctly and
is functional. Production test is not intended to validate that the board fulfills the complete IEEE 802.1.5.4
Standard requirements. Though the production tests are similar to those used when certifying an IEEE
802.15.4 Standard design, these tests are minimized to shorten overall testing time. The goal of production
test is to exercise the IEEE 802.15.4 PHY layer (or radio) to validate the RF front end of the module.

To reduce testing time, not all 802.15.4 channels need to be tested. Testing just one, two, or three channels
should be enough. This also holds true for power levels.

NOTE

In recommending reduced RF production testing, Freescale assumes a
complete assessment and validation of the RF front end components and
design of the module has been accomplished, and the design has been fully
qualified.

4.7.1   Recommended Production RF Tests

For validation of the module assembly, the recommended RF tests are limited to:

- Relative TX output power
- Relative Receiver input sensitivity
- Packet Error Rate (PER)

In these tests note that relative TX power and RX sensitivity are stated. This is because accurate, absolute
power out and sensitivity measurements are very difficult without direct connection of the test instrument
to the DUT, and most modules do not have easy means for direct connection. Making radiated
measurements (although less accurate) are much easier and sufficient for the purpose of establishing
correct, functional assembly.

4.7.2   RF Test Means and Environment

Radiated signal strength between units is determinate on many factors including transmitted output power,
antenna type and orientation, distance between units, etc. As a result, the suggested means to establish
relative test limits is to use known good units (commonly called GOLDEN units) or use test instruments
with known parameters. For a test signal source, a known good "golden" module unit can be used or a
properly programmed vector signal generator tied to an antenna, and the signal generator must be capable
of sending proper IEEE 802.15.4 packets to establish both PER and receiver sensitivity. To measure DUT
transmit power, a golden unit or a spectrum analyzer with connected antenna can be used.

A mechanical fixture to hold the DUT in a repeatable, known position and orientation is required. Once this test fixture is established, it can be calibrated for relative RF performance against known units or standards. Possible means of DUT-to-test unit communication can include:

- Golden unit to DUT - the golden unit can be located in close proximity to the DUT fixture (perhaps antenna-to-antenna), and the configuration calibrated through known good characterized units.

- RF test pad (plus test instrument) to DUT - Flat type antenna couplers mounted on a test pad are available. A custom mechanical mounting on the pad for the DUT can be added to provide repeatable measurements. The antenna coupler is connected via cable to proper test instrumentation. TESCOM Co., Ltd. (http://www.tescom.co.kr) is one supplier of these and other RF test accessories.

- Antenna (plus test instrument) to DUT - A good antenna connected to the test instrumentation can be mounted in close proximity to the DUT. Again a good mechanical mounting for the DUT is required to provide repeatable measurements

On the manufacturing floor, the DUT can share the electromagnetic spectrum with other RF DUTs or test instrumentation. External sources of interference can be present, such as base stations, adjacent test systems, microwaves, phone systems, etc. These potential interferers must be taken into account because they can affect test effectiveness and consequently test results.

To sufficiently suppress these signals, use a custom or commercial shielded RF test chamber with at least 60 dB shielding isolation over the 2.4 GHz ISM bandwidth. One such commercial chamber is the R&S TS712X shielded RF test chamber. (http://www2.rohde-schwarz.com)

4.7.3   Test Instrumentation

The following table shows some recommended test instruments for testing the IEEE 802.15.4 PHY and MAC layer.

Table 4-1. Instruments Recommended for RF Test

Manufacturer	Test Instrument	Comments
Agilent Technologies	N4010A, 89600 VSA, MXA,	For testing PHY layer
National Instruments	5663 VSA, 5673VSG	For testing PHY and MAC layers
Rohde & Schwarz	FSU, FSQ , SMU,	For testing PHY layer
Tektronix	RTSA	For testing PHY Layer

4.8   Production Data and MAC Address Handling

Typically, every manufactured unit must have some unique parameters or identifiers stored for operation and/or traceablility. These parameters can include:

- Manufacturing date and site
- IC device version
- Software version
- Operational/radio settings

- IEEE 802.15.4 MAC address - all IEEE 802.15.4 Standard devices must have a unique MAC address that individually identifies the device in the network.

Freescale's MAC and MAC-based solutions (RF4CE, SynkroRF, MAC, BeeStack) have been designed to support these unique parameters. Contained within the MAC is a "PRODUCTION DATA TABLE" that resides at a fixed NVM address range (each platform uses a different address range). This table allows for the production test flow to modify the target application binary for each unique unit. Two general means are used to customize the table:

- Directly modify the target download application binary - if the DUT NVM has not been previously loaded with the target application binary, it must be loaded into the DUT as part of the test flow (usually a final step). The application binary can be modified immediately preceding this step and then the customization is included as part of the normal download process.

- Directly load the production data table (or some of its elements) into NVM after test - if a "generic" DUT application binary has been previously loaded into the NVM either before assembly or is loaded as part of the test flow, the customized NVM location unique to each device must be left unprogrammed. The test application running on the MCU can then load a table into NVM or just those elements unique to a given DUT.

The table location NVM address and means to load the table are different based on the target platform. The following sections describe the process for the HCS08 and ARM7 platforms.

NOTE

- These descriptions are limited to the Freescale 802.15.4 MAC and MAC-based stacks. Other Freescale software offerings such as the SMAC and 22x-SMAC did not support these structures and providing equivalent functionality is left as an exercise for the user.

- The user is advised to always check the latest revision of software/database for changes to production table location and/or parameters. These may be subject to change.

4.8.1 HCS08 Parameters

For the HCS08-based platforms (GT60, MC1321x, QE128 MCU, etc.):

- The production data table is called FREESCALE_PROD_FLASH and resides at NVM address range 0xFF50 to 0xFFAF.
  — This declaration is found in the PLM\PRM\Linker.prm linker file of the Codewarrior project
  — The linker file also directs that the FREESCALE_PROD_DATA (the production parameters) be loaded into the FREESCALE_PROD_FLASH area

- The C code data structures used to define version strings and hardware parameters are found in the PLM\Interface\NV_Data.h file
  — They are used to declare the FREESCALE_PROD _DATA segment; also in the NV_Data.h file.
  — Observe use of a 5-byte "Delim" ASCII string at the beginning and end of the parameters table to delimit the table and allow an application to find the table contents if it moves address
  — The data structures are as follows:

```
           *************************************************************************/

           /* The Freescale version string struct is placed at a specific location in */
           /* ROM by the linker command file, and is normally only written during */
           /* manufacturing. */
           typedef struct FreescaleVersionStrings_tag {
             uint16_t NV_RAM_Version;
             uint8_t MAC_Version[4];
             uint8_t PHY_Version[4];
             uint8_t STACK_Version[4];
             uint8_t APP_Version[4];
             uint8_t HWName_Revision[4];
             uint8_t SerialNumber[4];
             uint16_t ProductionSite;
             uint8_t CountryCode;
             uint8_t ProductionWeekCode;
             uint8_t ProductionYearCode;
             uint8_t MCU_Manufacture;
             uint8_t MCU_Version;
             uint8_t NOT_USED;
           } FreescaleVersionStrings_t;

           /* The HardwareParameters_t struct is treated specially by both the */
           /* linker command file and the startup (crt0.c) code. See the comments */
           /* in crt0.c. */
           /* The initialString and terminalString are unsigned chars, instead of */
           /* uint8_t, because the C standard guarantees the sizeof(unsigned char). */
           /* These strings are needed by the startup code to locate the current */
           /* copy of the structure in NV storage, if there is one, and must be the */
           /* first and last fields in the type. */
           #define gaHardwareParametersDelimiterString_c   "Delim"
           typedef struct HardwareParameters_tag {
             unsigned char initialString[ sizeof( gaHardwareParametersDelimiterString_c )];
             uint8_t Bus_Frequency_In_MHz;
             uint16_t Abel_;
             uint16_t Abel_HF_Calibration;
           #ifdef PROCESSOR_QE128
             uint8_t NV_ICSC1;
             uint8_t NV_ICSC2;
             uint8_t NV_ICSTRM;
             uint8_t NV_ICSSC;
           #else
             uint8_t NV_ICGC1;
             uint8_t NV_ICGC2;
             uint8_t NV_ICGFLTU;
             uint8_t NV_ICGFLTL;
           #endif
             uint8_t MAC_Address[8];
             uint8_t defaultPowerLevel;
             uint8_t useDualAntenna;
             uint8_t paPowerLevelLimits[16];
             unsigned char terminalString[ sizeof( gaHardwareParametersDelimiterString_c )];
             } HardwareParameters_t;

           /*************************************************************************
```

- Table 4-2 provides a list of the version string and hardware parameters and their suggested usage. A number of parameters are recommended as Freesacle reserved, meaning they will be set via the software tools. Others are available to the user -
  — The user version parameters may be established at the application build/compile time and may not need to be set by the actual test flow
  — The **Abel_HF_Calibration** parameter is the 8-bit oscillator trim value that gets loaded into the transceiver register
  — The **MAC_Address[8]** parameter is the 8-byte MAC address used by the MAC function

Table 4-2. HCS08 Version String and Hardware Parameters Listing

Version/Parameter Name	No of Bytes	Suggested Usage
NV_RAM_Version	2	FSL Reserved
MAC_Version[4]	4	FSL Reserved
PHY_Version[4]	4	FSL Reserved
STACK_Version[4]	4	FSL Reserved
APP_Version[4]	4	User optional
HWName_Revision[4]	4	User optional
SerialNumber[4]	4	User optional
ProductionSite	2	User optional
CountryCode	1	User optional
ProductionWeekCode	1	User optional
ProductionYearCode	1	User optional
MCU_Manufacture	1	FSL Reserved
MCU_Version	1	FSL Reserved
NOT_USED	1	User optional
Bus_Frequency_In_MHz	1	FSL Reserved
Abel_Clock_Out_Setting	2	FSL Reserved
Abel_HF_Calibration	1	User optional / oscillator trim
NV_ICSC1 / NV_ICGC1	1	FSL Reserved
NV_ICSC2 / NV_ICGC2	1	FSL Reserved
NV_ICSTRM / NV_ICGFLTU	1	FSL Reserved
NV_ICSSC / NV_ICGFLTL	1	FSL Reserved
MAC_Address[8]	8	User optional
defaultPowerLevel	1	FSL Reserved
useDualAntenna	1	FSL Reserved
paPowerLevelLimits[16]	16	FSL Reserved

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- The FREESCALE_PROD_DATA table (or segment) values are normally assigned/defined in the PLM\Source\Common\Sys\NV_Data.c file. Any custom user parameters that are not DUT dependent can be pre-assigned.

- DUT-dependent FREESCALE_PROD_DATA table parameters (typically a custom trim Abel_HF_Calibration and MAC_Address) can be loaded into the target NVM by the test flow in a number of ways:

  — Modify the target S-record (application.s19) file before the application gets loaded to the DUT - the s19 file can be loaded via the BDM debug tool or other applications

  — Define the custom parameter NVM byte locations as 0xFF (unprogrammed NVM state) in the source, so that if the application image is preloaded to the NVM these bytes can be programmed later via a test utility program - the user must be sure to know the actual physical address(es) of the parameters to be written later

  — Load the parameters as a block after the target application image has been loaded - use a utility running in RAM to write the parameters as a block.

Freescale's Test Tool can assist in validating that the information was stored correctly. Use the firmware loader for the HCS08 and load the NVM Information. The file generated from this application contains the NVM production data section of the .S19 file. The following figure shows the NVM parameters window in Test Tool.
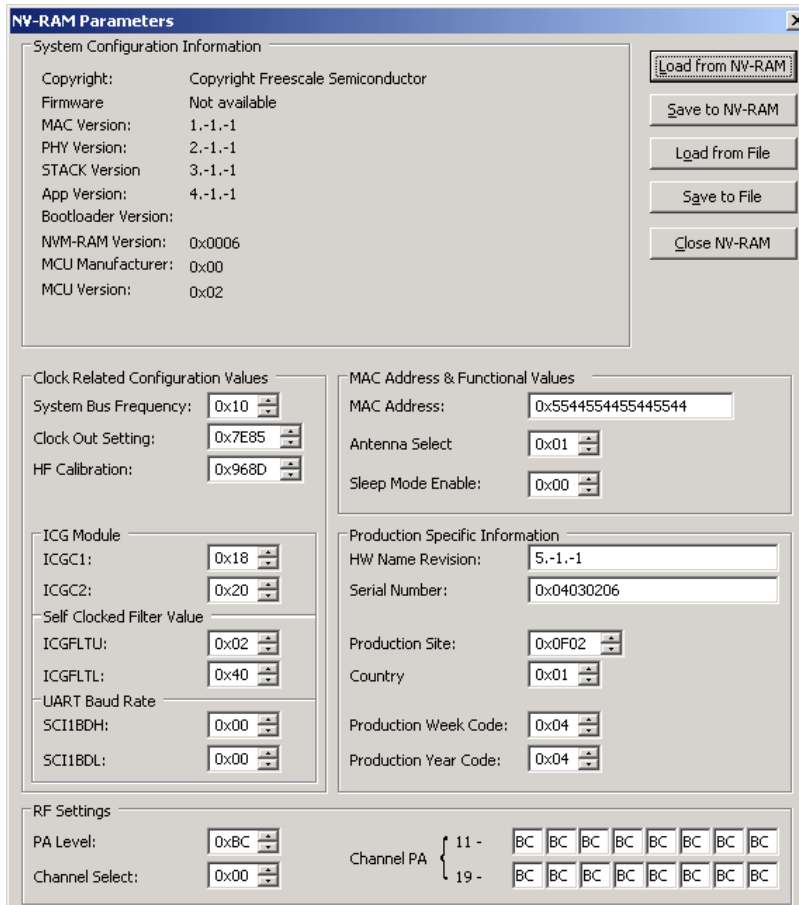

Figure 4-1. Test Tool NVM-Parameters Window

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4.8.2   ARM7 (MC1322x) Parameters

For the ARM7-based platforms (MC1322x):

- The production data table is called "nv_data_init_struct" and resides at serial NVM address range 0x00400800 to 0x004008FF.
  — This declaration is found in the `PLM\Icf\MC1322x-RAM-ROM.icf` linker file of the IAR tools project
  — The linker file also directs that the "nv_data_init_struct" (the production parameters) be loaded into the "INIT_region" which is also defined as the address range of 0x00400800 to 0x004008FF in the linker file.
- The C code data structures used to define version strings and hardware parameters are found in the PLM\Interface\`NV_Data.h` file
  — They are used to declare the nv_data_init_struct segment; defined in the PLM\Source\Common\Sys\`NV_Data.c` file.
  — Observe use of a 5-byte "Delim" ASCII string at the beginning and end of the parameters table to delimit the table and allow an application to find the table contents if it moves address
  — The data structures are as follows:

```
                **************************************************************************/

    /* The Fresscale version string struct is placed at a specific location in */
    /* ROM by the linker command file, and is normally only written during */
    /* manufacturing. */
    typedef struct FreescaleVersionStrings_tag {
      uint16_t NV_RAM_Version;
      uint8_t MAC_Version[4];
      uint8_t PHY_Version[4];
      uint8_t STACK_Version[4];
      uint8_t APP_Version[4];
      uint8_t HWName_Revision[4];
      uint8_t SerialNumber[4];
      uint16_t ProductionSite;
      uint8_t CountryCode;
      uint8_t ProductionWeekCode;
      uint8_t ProductionYearCode;
      uint8_t MCU_Manufacture;
      uint8_t MCU_Version;
      uint8_t NOT_USED;
    } FreescaleVersionStrings_t;

    /* The HardwareParameters_t struct is treated specially by both the */
    /* linker command file and the startup (crt0.c) code. See the comments */
    /* in crt0.c. */
    /* The initialString and terminalString are unsigned chars, instead of */
    /* uint8_t, because the C standard guarantees the sizeof(unsigned char). */
    /* These strings are needed by the startup code to locate the current */
    /* copy of the structure in NV storage, if there is one, and must be the */
    /* first and last fields in the type. */
    #define gaHardwareParametersDelimiterString_c   "Delim"
    typedef struct HardwareParameters_tag {
      unsigned char initialString[ sizeof( gaHardwareParametersDelimiterString_c )];
```

```
uint8_t  Bus_Frequency_In_MHz;
uint8_t  MAC_Address[8];
uint8_t  defaultPowerLevel;
uint8_t  dualPortRFOperation;
uint8_t  paPowerLevelLimits[16];
uint8_t  ccaThreshold;
bool_t   enableComplementatyPAOutput;
bool_t   gSystemClock24MHz_c;
uint8_t  gXtalCTune_c;
uint8_t  gXtalFTune_c;
uint8_t  gDigitalClock_PN_c;
uint8_t  gDigitalClock_RN_c;
uint16_t gMACA_Clock_DIV_c;
uint32_t gDigitalClock_RAFC_c;
uint8_t  gaRFSynVCODivI_c[16];
uint32_t gaRFSynVCODivF_c[16];
uint8_t  paPowerLevelLock;
unsigned char terminalString[ sizeof( gaHardwareParametersDelimiterString_c )];
} HardwareParameters_t;
/******************************************************************************
```

- Table 4-3 provides a list of the version string and hardware parameters and their suggested usage. A number of parameters are recommended as Freesacle reserved, meaning they will be set via the software tools. Others are available to the user -
  — The user version parameters may be established at the application build/compile time and may not need to be set by the actual test flow
  — The **gXtalCTune_c** and the **gXtalFTune_c** parameters are the coarse and fine oscillator trim values that get loaded into the XTAL_CNTL register
  — The **MAC_Address[8]** parameter is the 8-byte MAC address used by the MAC function

Table 4-3. ARM7 Version String and Hardware Parameters Listing

Version/Parameter Name	No of Bytes	Suggested Usage
NV_RAM_Version	2	FSL Reserved
MAC_Version[4]	4	FSL Reserved
PHY_Version[4]	4	FSL Reserved
STACK_Version[4]	4	FSL Reserved
APP_Version[4]	4	User optional
HWName_Revision[4]	4	User optional
SerialNumber[4]	4	User optional
ProductionSite	2	User optional
CountryCode	1	User optional
ProductionWeekCode	1	User optional
ProductionYearCode	1	User optional
MCU_Manufacture	1	FSL Reserved

Table 4-3. ARM7 Version String and Hardware Parameters Listing

Version/Parameter Name	No of Bytes	Suggested Usage
MCU_Version	1	FSL Reserved
NOT_USED	1	User optional
Bus_Frequency_In_MHz	1	FSL Reserved
MAC_Address[8]	8	User optional
defaultPowerLevel	1	FSL Reserved
dualPortRFOperation	1	FSL Reserved
paPowerLevelLimits[16]	1	FSL Reserved
ccaThreshold	1	FSL Reserved
enableComplementatyPAOutput	1	FSL Reserved
gSystemClock24MHz_c		FSL Reserved
gXtalCTune_c	1	User optional / oscillator coarse tune
gXtalFTune_c	1	User optional / oscillator fine tune
gDigitalClock_PN_c	1	FSL Reserved
gDigitalClock_RN_c	1	FSL Reserved
gMACA_Clock_DIV_c	2	FSL Reserved
gDigitalClock_RAFC_c	4	FSL Reserved
gaRFSynVCODivI_c[16]	16	FSL Reserved
gaRFSynVCODivF_c[16]	16	FSL Reserved
gaRFSynVCODivF_c[16]	16	FSL Reserved

- The **nv_data_init_struct** table (or segment) values are normally assigned/defined in the PLM\Source\Common\Sys\NV_Data.c file. Any custom user parameters that are not DUT dependent can be pre-assigned.
- DUT-dependent **nv_data_init_struct** table parameters (typically custom oscillator trim and MAC_Address) can be loaded into the target NVM by the test flow in a number of ways:
  — Modify the target binary file before the application gets loaded to the DUT - the file can be loaded via the JTAG debug tool or other applications
  — Define the custom parameter NVM byte locations as 0xFF (unprogrammed NVM state) in the source, so that if the application image is preloaded to the NVM these bytes can be programmed later via a test utility program - the user must be sure to know the actual physical address(es) of the parameters to be written later
  — Load the parameters as a block after the target application image has been loaded - use a utility running in RAM to write the parameters as a block.

For the MC1322X, Freescale's Test Tool can assist in validating that the MAC address information was stored correctly. Use the firmware loader for the MC1322x. Once the bin file is selected, the MAC address

section displays the current DUTs MAC Address. Test Tool is not intended to be used for mass production but only as a diagnostic and repair tool.

4.9   Simple Overview of Test Flow

Each situation will be different based on the application, but Table 4-4 provides a simple overview of a typical test flow.

Table 4-4. Simple Test Flow

Feature Component	Test	Test Preconditions Input Stimulation	Expected Result Comments
Power supply	Voltage	• Check main Module DC voltages. • Use DMM to measure voltage across different TP's	Voltages are within specs.
	Current	• Check main Module DC Currents. • The insertion of current breakthroughs and dedicated voltage networks to the IC, eases testing.	Currents are within specs.
Programming test software	Program Testing image	• Using serial debug port, program test firmware to NVM or RAM as appropriate to exercise all the peripherals in use by the applications software	Testing successful. Include a register-based flag to indicate the testing was successful. **Note:** The testing required for MCU peripherals and asociated external circuitry is totally dependent on the user application.
Reference Oscillator Crystal Trim	Trim	• PTEQ Firmware outputs the defined "Crystal Frequency" or a multiple of it through a GPIO or a defined test pin • Use Frequency Counter to measure frequency • If F_{MHz_in} > Crystal Frequency ± 10ppm • Then adjust XTAL trim values until • F_{MHz_in} < Crystal_Frequency ± 10ppm • Store XTAL_TRIM	F_{MHz_in}<= Crystal_ frequency ± 10ppm. Save XTAL_TRIM
RF RX	RF Receiver Tests	• Using PTEQ Firmware set the DUT in the receiver mode. • Set the DUT to perform a PER. • Set the VSG to send 1000 packages, 20 kbytes payload. • Relative P_{out} to set actual received power to about -90dBm • Perform the PER on desired Channels	$PER_{CH\,A@-90}$ < 1% $PER_{CH\,B@-90}$ < 1% $PER_{CH\,C@-90}$ < 1%

Table 4-4. Simple Test Flow

Feature Component	Test	Test Preconditions Input Stimulation	Expected Result Comments
	RF Transmitter Tests	• Using PTEQ Firmware set the DUT in the transmitter mode. • Set the DUT in continuous unmodulated wave • Nominal Power • Using the VSA • Measure Output power	$VSA\_UN_{CH\ 20} = 0$ dBm
		• Set the DUT to send PER packetts • Measure PER < 1% at test instrument	$PER_{CH\ A} < 1\%$
Programming	FLASH Final Application with MAC Address	Using serial debug port, program FLASH Final Application. Additional program NVM device dependent parameters as required	Programmed successfully
Print Label	Label with Factory defined values	For every DUT that passes all the previous functional tests, a Label containing the MAC address, the crystal trim and the serial number	Print Label

Appendix A
Freescale 802.15.4 RF Test Software

A.1   Test Applications and Tools Overview

The RF test software ranges from simple standalone applications running on the target board to more capable and sophisticated tools that use a client application running on the target board with host application running on a personal computer (PC).

A.1.1   Target Applications for RF Test

Table A-1 lists the software target applications recommended for test or modification for test. These are applications that run on the platform MCU on the target board.

NOTE

These applications all assume use of Freescale's Beekit Wireless Connectivity Toolkit software tools.

Table A-1. Freescale 802.15.4 Recommended Software Apps for RF Test

Application	Description	Platform	Docu-mentation	Suitable for
Test Mode application	SMAC application that allows PHY level testing on all channels through button presses. Includes PBRS9, RX, TX with Modulation, CW.	HCS08	AN3231	Hardware evaluation, FCC pre-cert
Basic Packet Error Test	SMAC application that send 1000 packets of 20 byte payload. Operates with USB PC connection or with button presses.	HCS08	AN3231	Engineering or production Range testing
Range Demonstration Plus	SMAC application that provides LED indication of LQI	HCS08	AN3231	Range testing
ZigBee Test Client (ZTC)	MAC and BeeStack application that supports the features of Test Tool. Can be used with a customer host via UART.	HCS08, ARM7	ZigBee Test Client Reference Manual (ZTCRM)	Hardware evaluation, FCC pre-cert, starting point for production test firmware
Connectivity Test	SMAC application that allows Radio Testing, reference oscillator frequency measurement and adjustment, PER and LQI vs range measurement. Interface is selectable between button pushes or UART.	ARM7	MC1322x SMAC Demonstation Application User Guide (22xSMACDAUG)	ARM7 hardware evaluation and FCC testing

A.1.2   PC Host Application for Test (Test Tool)

Test Tool is a Freescale provided Windows® based graphical interface utility that communicates with 802.15.4 target development and applications boards. Test Tool provides the following features:

- Command Console — Allows users to send and receive commands from a PC to a Freescale 802.15.4 development board through a virtual COM port (VCP)
- Script Server — Allows users to load, execute, and review results of Python Scripts and Test Sets.
- HCS08 Firmware Loader — Allows users to flash different application code into Freescale HCS08 based development boards from Test Tool using a USB multilink device (BDM)
- MC1322x Firmware Loader - Allows users to load application code into either RAM or flash memory of MC1322x ARM7 based development boards, using a USB or serial cable connected to the board's communication port
- Radio Test — Allows users to run various radio tests employing just one board for various radio tests or Packet Error Rate (PER) tests employing two boards. The Radio Test mode adjusts to the board type under test (HCS08 or MC1322x ARM7)

Test Tool must be used with an appropriate client application on the target/development board. In the list of applications from Table A-1, ZigBee Test Client (ZTC) is the proper client. Radio test capability is a subset of the full functionality of this client application.

A.2   SMAC Test Applications for HCS08 Platform

Use of the Freescale Beekit applications is based on the different codebases. The "HCS08 SMAC Codebase x.x.x" for the HCS08 platform is a Freescale proprietary protocol meant for simple applications and supports several simple test applications:

- **Test Mode** - This application is a simple tool for testing basic RF transmitter performance. Operation of the application is controlled by push button switches to select radio channel (frequency) and TX mode. The supported modes are:
  - Idle - no TX output; radio not active
  - TX 9th Order Binary Polynomial (PRBS9) - TX output is continuous stream of packet with PRBS9 random data
  - RX_ON - no TX output; radio in RX mode
  - TX_ON with modulation - TX output is continuous carrier with modulation
  - TX_ON Continuous Wave (CW) without modulation - TX output is continuous carrier with no modulation
- **PER Test RX** / **PER Test TX** - These apps are the RX application and the TX application for a basic packet error rate (PER) test. The TX application is loaded into the transmitting node and the RX application is loaded into the receiving node. An individual test sends 1000 packets each with a 20-byte payload on a single channel. Although there is a standalone mode, a PC may be used for reporting test results. Supported features are:
  - Communication with a PC through a USB virtual Com Port (VCM)
  - Control by 2 switches to change channel and start test
  - Four Channels or frequencies used; 2405 GHz, 2430 GHz, 2455 GHz, and 2480 GHz

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— PC COM port reports: 1) number of packets received, 2) Length of packet, 3) link quality (LQI), cyclical redundancy check (CRC), and load data

- **Range Demo Plus -** This application is constructed of two binary images that get loaded on two separate boards:
  - The TX range demo plus application (TX_APP)
  - The RX range demo plus (RX_APP)

The TX_APP repeatedly transmits packets (with ACK enabled) at a given rate. The RX_APP receives a given packet and responds with an "ACK" frame. The ACK differs based on the strength of the received TX packet as measured by the TX packet LQI. For field testing, LEDs on both boards are flashed in a manner to indicate both successful transmission and relative signal strength. In the field, the user can then change the distance between boards to get a measure of usable range.

A.3   22xSMAC Test Application for ARM7 Platform (Connectivity Test)

Connectivity Test is based on the 22xSMAC codebase for the ARM7 platform. This application allows evaluation of the basic connectivity between two transceivers. Separate transmitter and receiver target modules with suitable applications are required. The connectivity test supports the following functionality:

- Configure the transceiver in a specific test mode in order to test the transmitter RF performance - available test modes are:
  - Modulated transmission
  - Unmodulated transmission
  - Pulse PRBS9 transmission (TX 9th Order Binary Polynomial)
  - Idle (no TX output)
- Packet Error Rate (PER) test - measures the percentage of packet losses over a certain channel. Also reports the Link Quality Indicator (LQI) of each packet received.
- Range test - reports the Link Quality Indicator of a signal; can be used as a range test.
- Other parameters, such as the channel and power can be modified to allow testing on channels with different power values.
- Reference oscillator trim - a programmed timer output pin is provided to measure reference oscillator frequency accuracy (ppm) and to trim the frequency as necessary.

Two possible interfaces are implemented; a manual interface through push buttons or a serial interface port (UART) that is menu driven. Only one interface can be selected at a time (the interface type is selected when creating the project within BeeKit).

Connectivity Test is a useful application for simple development and first evaluation of RF characteristics of a new target design/layout. It is also easily modified or expanded by the user to add tests.

A.4 ZigBee Test Client (ZTC)

The Freescale ZigBee Test Client (ZTC) diagnostic tool is primarily intended for extensive testing of the BeeStack protocol layer interfaces. Used with the Freescale Test Tool PC software, through the ZTC client application a user can start/implement a network, and run any of the over 300 commands to test the BeeStack application services and interfaces. Part of this capability is an RF test suite called "Radio Test" that is an integral function within Test Tool. The capabilities of radio test are similar to other applications:

- Radio test including transmitter
- Packet error rate
- Setting board parameters including trimming the reference oscillator
- Reading/writing device registers

ZTC and Test Tool together provide a more capable and sophisticated environment that the other discussed applications. This environment can be extended for FCC certification and for module production testing.

Appendix B
RF Test Modes in The MC1320x and MC1321x Transceivers

B.1   Introduction

The Freescale MC1320x family and MC1321x family 802.15.4 transceivers support certain RF test modes. Although Freescale provides software applications that enable RF test modes, it is the intent of this appendix to provide background information on hold to enable these RF test modes.

B.2   SPI Registers That Support RF Test

The 20x and 21x transceivers share the same SPI register model. Table B-1 list registers that impact RF test and reference oscillator trim.

Table B-1. Modem SPI Register Table

REGISTER NAME	Add (Hex)	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Default
Control_B	07	tmr_load	ct_bias_en	ct_bias_inv	RF_switch_mode	miso_hiz_en		clko_doze_en		tx_done_mask	rx_done_mask	use_strm_mode				hib_en	doze_en	0x0C00
PA_Enable	08	pa_en																0xFFF7
CLKO_Ctl	0A	xtal_trim[7:0]											clko_rate[2:0]					0x7E86
BER_Enable	30	ber_en																0x0004
PSM_Mode	31											psm_tm[2:0]						0xA000

The Control_B Register 0x07 controls the RF mode of operation, i.e., single port vs dual port and use of the CT_Bias pin. Also, the 16MHz crystal trim field is found in the CLKO_Ctl Register 0x0A. These registers, however, are typically not affected by RF testing.

Table B-2 lists the bit fields useful for controlling the transceiver for RF tests.

Table B-2. Transceiver SPI Register Fields Useful for RF Test

Field	Register	Bit(s)	Default	Description
pa_en	0x08	15	0b1	Power amp (PA) enable - when pa_en = 1, the TX PA is enabled. When pa_en = 0, the transmitter puts out no power.
ber_en	0x30	15	0b0	Bit error rate test enable - when ber_en = 1, the transceiver is put in continuous receive or transmit mode. Continuous TX mode is useful for current measurements or for looking at the TX spectrum. Continuous RX mode is useful for current measurements.
psm_tm[2:0]	0x31	5-3	0b000	Phase shift modulator test mode - only two modes are used for this field. When psm_tm[2:0] = 0b000, this is normal operation (normal modulation). When psm_tm[2:0] = 0b001, the modulator is disabled and the transmitter puts out an unmodulated signal.

B.3   Programming the Transceiver for Test Modes

The MC13202 and MC1321x transceivers are capable of two data transfer modes: (Packet Mode and Streaming Mode). The MC13201 transceiver supports only Packet Mode. The Packet Mode is often used to implement the RF test modes. The RF modes are activated by setting appropriate control bits and then invoking RX or TX packet data mode.

B.3.1   Transmitter Test Modes

There are several transmitter modes that are useful for testing RF output spectrum.

B.3.1.1   Continuously Transmit Unmodulated Carrier

It is possible to transmit a continuous, unmodulated signal. This mode is useful for observing transmitter center frequency and measuring TX current for the transceiver. Packet transmit mode is used. The steps to implement this mode include first sending a dummy packet to setup the TX analog circuitry, next disabling the modulator, and then turning on continuous transmit mode:

- Setup TX analog circuitry by sending a dummy packet
  - Disable the PA (write pa_en, Register 0x08, Bit 15 = 0).
  - Set the message field length to a short number (frame length of 4 is a good example).
  - Transmit dummy message (PA is off) to setup TX analog circuitry (use packet mode and no data needs to be loaded because dummy data is sufficient).
  - Wait for transmission completion (this can be interrupt driven by waiting for tx_done IRQ).
- Enable the PA (write pa_en, Register 0x08, Bit 15 = 1).
- Enable the continuous TX mode (write ber_en, Register 0x30, Bit 15 = 1).
- Disable the phase shift modulator (write psm_tm[2:0], Register 0x31, Bits 5-3 = 0b001).
- Enable the transmitter with a TX operation which will be continuous and without modulation (RXTXEN must be high and set xcvr_seq[1:0] to TX mode).

The TX operation will continue until aborted.

B.3.1.2   Continuously Transmit Modulated Carrier

It is possible to transmit a continuous, modulated signal. Packet transmit mode is used. The data pattern sent is a repeating sequence of the two (2) symbols stored in tx_pkt_ram[15:0], Register 0x02. The steps to implement this mode include first sending a dummy packet to setup the TX analog circuitry and then turning on continuous transmit mode:

- Setup TX analog circuitry by sending a dummy packet
  - Disable the PA (write pa_en, Register 0x08, Bit 15 = 0).
  - Set the message field length to a short number (frame length of 4 is a good example).
  - Transmit dummy message (PA is off) to setup TX analog circuitry (use packet mode and no data needs to be loaded because dummy data is sufficient).
  - Wait for transmission completion (this can be interrupt driven by waiting for tx_done IRQ).
- Load desired 2 TX symbols into tx_pkt_ram[15:0] (these 2 symbols will get continuously repeated).
- Enable the PA (write pa_en, Register 0x08, Bit 15 = 1).
- Enable the continuous TX mode (write ber_en, Register 0x30, Bit 15 = 1).
- Enable the transmitter with a TX operation which will be continuous and with modulation as determined by the data word (RXTXEN must be high and set xcvr_seq[1:0] to TX mode).

The TX operation will continue until aborted.

B.3.1.3   Transmit PRBS9 Data Packet Data

It is useful to repeatedly transmit a known data packet for observing transmitter characteristics as part of radio certification. The packet uses pseudo-random binary sequence (PRBS) data generated via a maximal length 9th order binary polynomial (PRBS9). The packet length is set to the maximum length of 127 bytes (including the two CRC data bytes).

When using packet transmit mode, the following steps assume default operation of the transceiver (PA enabled, ber_en off, and modulator enabled) and include:

- Generate 125-byte data buffer based on a PRBS9 algorithm (such as $x^9 + x^5 + 1$ polynomial).
- Load data buffer into tx_packet_ram[15:0].
- Set message field length to 127 (maximum length).
- Enable the transmitter with a TX operation which will be normal with modulation (RXTXEN must be high and set xcvr_seq[1:0] to TX mode).
- Wait for transmission completion (this can be interrupt driven by waiting for tx_done IRQ).
- To repeat the transmission, again enable the transmitter with a TX operation.

PBRS9 can also be sent via the streaming data packet mode (with the same message parameters) as would be used with the 802.15.4 MAC services.

B.3.2   Receiver Test Mode

Other than normal operation, there is one additional receive test mode that is useful. A continuous receive mode can be enabled that turns on the analog receive circuitry and leaves it on. This is useful for measuring current in RF receive mode.

The steps include enabling a receive with the ber_en bit set:

* Enable the continuous RX mode (write ber_en, Register 0x30, Bit 15 = 1).
* Enable the receiver with a RX operation which will be continuous (RXTXEN must be high and set xcvr_seq[1:0] to RX mode).

Packet error rate (PER) is used to measure normal receiver operation. A true <u>bit error rate</u> is not possible for the receiver because no direct access to the decoded bit stream is given.